Data-Centric Network of Things

A Method for Exploiting the Massive Amount of Heterogeneous Data of Internet of Things in Support of Services

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Academic dissertation for the Degree of Doctor of Philosophy in Computer and Systems Sciences at Stockholm University to be publicly defended on Tuesday 13 June 2017 at 13.00 in Lilla hörsalen, NOD-huset, Borgarfjordsgatan 12.

Abstract

Internet of things (IoT) generates massive amount of heterogeneous data, which should be efficiently utilized to support services in different domains. Specifically, data need to be supplied to services by understanding the needs of services and by understanding the environment changes, so that necessary data can be provided efficiently but without overfeeding. However, it is still very difficult for IoT to fulfill such data supply with only the existing supports of communication, network, and infrastructure; while the most essential issues are still unaddressed, namely the heterogeneity issue, the recourse coordination issue, and the environments' dynamicity issue. Thus, this necessitates to specifically study on those issues and to propose a method to utilize the massive amount of heterogeneous data to support services in different domains.

This dissertation presents a novel method, called the data-centric network of things (DNT), which handles heterogeneity, coordinates resources, and understands the changing IoT entity relations in dynamic environments to supply data in support of services. As results, various services based on IoT (e.g., smart cities, smart transport, smart healthcare, smart homes, etc.) are supported by receiving enough necessary data without overfeeding.

The contributions of the DNT to IoT and big data research are: firstly the DNT enables IoT to perceive data, resources, and the relations among IoT entities in dynamic environments. This perceptibility enhances IoT to handle the heterogeneity in different levels. Secondly, the DNT coordinates IoT edge resources to process and disseminate data based on the perceived results. This releases the big data pressure caused by centralized analytics to certain degrees. Thirdly, the DNT manages entity relations for data supply by handling the environment dynamicity. Finally, the DNT supply necessary data to satisfy different service needs, by avoiding either data-hungry or data-overfed status.

Keywords: *Internet of Things, Big Data, Artificial Intelligence, Data Supply, Distributed System.*

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Sammanfattning

Sakernas Internet (IoT) genererar löpande stora mängder heterogena data. Dessa bör utnyttjas effektivt för att stödja tjänster inom olika områden. Intelligent distribution av data är nödvändigt utan den leder till övermättnad . Det är emellertid svårt att uppfylla kraven på en datacentrisk design inom IoT enbart med stöd av nätverkskommunikation. Viktiga delar som behandlar dataheterogenitet, samordning och olika miljöers dynamik har inte fått tillräckligt stort fokus. Följaktligen finns det behov av att specifikt studera dessa delar och föreslå en metod för att kunna utnyttja större mängder heterogena data, i syfte att stödja tjänster inom olika domäner.

I den här avhandlingen presenteras en ny metod som kallas data-centric network of things (DNT). Den bygger på en förståelse för förändringar av IoT-enheters relationer i dynamiska miljöer och fokuserar på samordning av resurser och intelligenta leveranser av data till supporttjänster. Som ett resultat kan olika IoT-baserade tjänster, såsom smarta städer, smarta transporter, smart sjukvård samt smarta hem, stödjas genom att nödvändig data tillhandahålls i lagom mängd.

Avhandlingens bidrag till forskningen inom IoT och storskalig dataanalys är fyrfaldigt. För det första gör DNT det möjligt att uppfatta IoT-data och IoT-resurser samt relationer mellan IoT-enheter i dynamiska miljöer. Denna perception kan användas för att hantera heterogenitet på olika nivåer inom IoT. För det andra samordnar DNT IoT edge-resurser för att bearbeta och sprida data baserat på möjligheten till uppfattning, vilket i viss utsträckning minskar det stora datatryck som orsakas av centraliserade Big Data-analyser. För det tredje underlättar DNT administrationen av relationer mellan IoT-enheter ur dataförsörjningshänseende genom att hantera olika miljöers dynamik. Slutligen stöder DNT en typ av dataleveranser som uppfyller olika servicebehov och skyddar samtidigt mot databrist och dataöverflöd.

Acknowledgments

In 2013, I started my four years' long journey for a Ph.D. As always, exploring is full of uncertainties and challenges. During this journey, I have been disappointed at times, when the negative results come. However, the darkness on this journey endows me with a pair of bright eyes that I use to move toward the light. The end of this journey is the start of another new brighter journey. I feel deeply grateful for the silent support and encouragement from my families, supervisors, and friends that enable me to go further!

First of all, I give my sincere gratitude to my dear parents, grandparents, and my dear uncle Lisheng Ding, for all the love, care, understanding, and silent support you endowed me with during this life.

Moreover, I would like to offer my sincere gratitude to my respected supervisors Associate Professor (Docent) Rahim Rahmani and Professor Theo Kanter and for their brilliant advice and solicitude. Without the support and encouragement of Associate Professor (Docent) Rahim Rahmani, I do not think I would be able to finish my doctorate research. I deeply appreciate Professor Vassilis Kostakos, who is the person that showed me the blueprint of research and motivated my eagerness to become a researcher. In addition, I deeply appreciate Professor Petri Pulli, who is the first person to lead me into scientific research.

In addition, I express my sincere gratitude to my dear friends Per Ahlgren, Yuhong Li, Kim Nevelsteen, Hasibur Rahman, Andreas Paulsson, and Maggie Feng; your friendship is the moonlight on my way when the road to the distant destination was dark.

After all, I sincerely offer my best wishes for all of them and for myself in the future journey of hope!

Bin Xiao
May 2017, Stockholm

List of Publications

This dissertation is based on the following papers (arranged chronologically by Roman numerals).

Paper I: **Constructing Context-centric Data Objects to Enhance Logical Associations for IoT Entities**

> **B. Xiao**, T. Kanter, and R. Rahmani, In *Procedia Computer Science* 52 (2015) 1095-1100, Elsevier, May 2014.

Paper II: **Logical Interactions for Heterogeneous IoT Entities via Virtual World Mirrors in Support of Ambient Assisted Living**

> **B. Xiao**, T. Kanter, and R. Rahmani, In *Journal Ambient Intelligence and Smart Environments*, IOS Press, issue Nov 2016, 2015.

Paper III: **Intelligent Data-intensive IoT: A Survey**

> **B. Xiao**, R. Rahmani, Y. Li, D. Gillblad, T. Kanter, In *Proceedings of International Conference on Computer and Communications*, IEEE, 2016.

Paper IV: **Edge-based Interoperable Service-driven Information Distribution for Intelligent Pervasive Services**

> **B. Xiao**, R. Rahmani, Y. Li, and T. Kanter, 2-nd review In *Journal Pervasive and Mobile Computing*, 2016.

Paper V: **A Deep Relation Learning Method for IoT Interoperability Enhancement within Semantic Formalization Framework**

> **B. Xiao** and R. Rahmani, *International Conference on Internet of Things, Data, and Cloud Computing*, ACM, 2016.

Paper VI: **Self-evolvable Knowledge-enhanced IoT Data Mobility for Smart Environments**

B. Xiao, Submitted to *International Conference on Internet of Things and Machine Learning*, ACM, 2017.

In addition to Papers I to VI, the following papers have been produced but are not included into this dissertation (arranged chronologically by alphabet):

Paper A: **Generic Distributed Sensing in Support of Context Awareness in Ambient Assisted Living**

B. Xiao, T. Kanter, and R. Rahmani, In *Multimedia and Ubiquitous Engineering* (pp. 99-107), Springer Berlin Heidelberg, May 2014.

Paper B: **An Ontology-based Problem-logic Driven Approach toward the Activity Awareness for Elderly Care**

B. Xiao, T. Kanter, and R. Rahmani, In *International Journal of Multimedia and Ubiquitous Engineering* 10(4) 31-42, 2015.

Paper C: **Vehicular Network Enabling Large-Scale and Real-Time Immersive Participation**

T. Kanter, R. Rahmani, Y. Li, and **B. Xiao**, In *Internet of Vehicles–Technologies and Services*, Springer International Publishing, 2014.

Author's Contributions

The contribution of each research paper in support of this dissertation is summarized as follows:

Paper I: **Constructing Context-centric Data Objects to Enhance Logical Associations for IoT Entities**

As both the first primary author and corresponding author of this paper, I contributed to this paper by proposing an alternative technique of semantically constructing context-centric data objects based on service logics for logical associations. This contextual data-object construction method enables an event net based on a logical association net adapted to the changing situations. Compared with the purely data-oriented and purely semantic-oriented associations from previous research, this proposed solution focuses on addressing the flexibility and dynamicity issues to make the association between entities evolve in a logical sense. Existing semantic solutions are faced with either flexibility or dynamicity challenges to discover and maintain the associations caused by many factors. Purely data-oriented association methods are limited in exploring new associations from existing associations. In addition, extremely small or extremely large datasets will affect the accuracy of such data-oriented methods, with the outputted associations based on statistic sense rather than logic sense.

Other co-authors have commented the draft and provided helpful suggestions for improvement.

Paper II: **Logical Interactions for Heterogeneous IoT Entities via Virtual World Mirrors in Support of Ambient Assisted Living**

As both the first primary author and corresponding author of this paper, I contributed to this paper by the following:

i) Proposed a solution to annotate the relations between entities in line with both the service logics and the dynamic environment. In addition, this work proposed logical object-oriented IoT entity interactions to support the coordination between IoT entities. Specifically, the research introduced entity mirror in the virtual world to emulate the heterogeneous behaviors of sensors and actuators in the physical world, based on which to establish the logical interactions to coordinate IoT entities.

ii) The entity mirror forms a graph based on the logical relations between different IoT entities and service logics. Therefore, the coordination between entities can focus on logic sense to satisfy different service requirements. Additionally, a resource retrieving tool is introduced to acquire physical entity resources based on the entity mirror in the virtual world, which enhances the interoperability between virtual and physical world.

Other co-authors have commented the draft and provided helpful suggestions for improvement.

Paper III: **Intelligent Data-intensive IoT: A Survey**

As both the first primary author and corresponding author of this paper, I contributed to this paper by:

i) Investigating and concluding the existing major views for handling IoT data and different intelligent enablers related to the data-intensive IoT. Based on that, the authors pointed out some challenges that have not been explored by analyzing the specialization of the data-intensive IoT.

ii) Based on the investigation and recognized shadow issues, the authors highlight some future directions for data-intensive IoT—an extended big data model for intelligent data-intensive IoT with three suggested essences: provide, prune, and pre-act.

Other co-authors have commented the draft and provided helpful suggestions for improvement.

Paper IV: **Edge-based Interoperable Service-driven Information Distribution for Intelligent Pervasive Services**

As both the first primary author and corresponding author of this paper, I contributed to this paper by:

i) Introducing a service-driven edge-based IoT to automatically initiate, configure, and adapt the relations for data distributions between heterogeneous entities in smart environments by working with context recognition, enhancing the interoperability between entities for data exchanging. Therefore, it deals with the limitations of the previous research that provide manual or semi-manual adaptation for interactions in different scenarios by enhancing the interoperability and dynamicity.

ii) Proposing a system architecture and mechanism to enable logic based self-adaptability for data distribution, circumventing the problem with dialects of heterogeneous entities that cause ambiguity. The system goes beyond previous research, as the context is multidimensional and no longer limited to simply user-relevant background information or human behavior. Hence, the presented IoT enabler can serve to control and manage entity interactions and communication, utilizing both internal and external context relevant to each entity. Thus, entities can be discovered and recommended for distributing data according to their individual status and global situations.

Other co-authors have commented the draft and provided helpful suggestions for improvement.

Paper V: **Strength the Semantic-based IoT Data Directing Using Deep Relation Recognizer**

As both the first primary author and corresponding author of this paper r, I contributed to this paper by proposing a deep recursive autoencoder-based method as an alternative solution to strengthen data directing for semantic-based IoT. Using the proposed solution, data can be directed according to the relations for enriching semantic enhancement. The recognizer first represents the virtual entities of IoT via feature extraction. Based on that, the recognizer is trained in a manner to consider the surrounding relations of the targeted entity

Other co-authors have commented the draft and provided helpful suggestions for improvement.

Paper VI: **Self-evolvable semantic-enhanced IoT data mobility for smart environments**

As the sole author of this paper, I contributed to this paper by proposing a method to update the entity relations of the system initialization. Specifically, the system can learn from the most current environments based on a deep architecture, based on which the existing knowledge base of entity relations can be updated, closely adhering to both service requirements and the surrounding status. Supported by such updating, the system can evolve and adapt according to the current surroundings to provide smart and environment-interpretable data mobility.

Contents

Abbreviations

ADAS	Advanced Driving Assistance System
DNT	Data-centric Network of Things
DHT	Distributed Hash Table
DSR	Design Science Research
IoT	Internet of Things
IP	Internet Protocol
SPSSE	Systems Providing Services

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Part I

Research Problems and Approach

1 Introduction

Data plays an essential role in supporting and driving various services in different domains (Sheth, 2016), such as smart vehicles, smart homes, etc. The Internet of things (IoT) has been commonly accepted as a proper paradigm for collecting and sharing data to support various services (Dahlberg & Glaumann, 2017). IoT generates and accumulates a massive amount of heterogeneous data from a vast number of devices, and it is very important to efficiently exploit the massive amount of heterogeneous data to support services (Paper III). Specifically, in the network of connected heterogeneous things, data need to be efficiently supplied for services by understanding the needs of services and by understanding the dynamic environment changes, so that necessary data can be provided enough but without overfeeding, which is defined as *data-centric* style.

For a long time, IoT has primarily been focusing on handling connectivity issues in the aspects of communication and infrastructure for data transmission. However, with only the supports of communication, network, and infrastructure, it is very difficult to efficiently exploit IoT data, in the described data-centric style. Recent discussions regarding IoT have started to emphasize the semantics for interoperable communication of IoT, which proposes establishing common understandings of communications between heterogeneous IoT components (Palavalli, Karri, & Pasupuleti, 2016)(Martín Serrano et al., 2015). However, the most essential issues are still unaddressed, namely the heterogeneity issue, the recourse coordination issue, and the environments' dynamicity issue. Thus, it is very important to study the issues mentioned above and propose the methods for supplying necessary data among the massive amount of heterogeneous data in support of services. Specifically, it is to solve the three "how" problems: how to perceive data, resources, and the relations among IoT entities in dynamic environments; how to coordinate resources for data supplying; and how to handle the environments' dynamicity.

This dissertation summarizes my research and presents the methods of data-centric network of things (DNT). The DNT utilizes the resources in the edge of IoT, which can strengthen the ability of IoT for handling the massive heterogeneous amount of data in data-centric style, to support various services in the digital age, for example, to supply data in an efficient and sufficient manner for smart urban services.

The coming sections of this chapter will first discuss the research background, articulate the motivations, and then analyze the existing problems in the research area. The research questions will be formulated. A brief overview of the methodology for the research will be further presented. The contributions of the research and its implications will be discussed. At the end of this chapter, the outline of the dissertation will be presented.

1.1 Background and Motivations

With the booming of various services in the digital age (Reinhard, Jesper, & Stefan, 2016), IoT is facing the pressure of the massive amount of heterogeneous data that have been generated in dynamic environments. This raises an unavoidable issue for IoT to intelligently exploit the data in support of various services for digitalization (Green, 2015)(Sheth, 2016) in the data-centric style, as defined above. Supplying data from IoT to support services is important for the systems providing services (SPSSE) to strengthen the ability to intelligently handle complex and dynamic environments. Furthermore, such data supply in data-centric style can enable comprehensively extended awareness scope of the SPSSE toward the environments into which the SPSSE is immersed. For example, conventional environment awareness systems of the smart vehicle primarily depend on collecting data from the locally deployed sensors on the vehicles, which has limitations regarding the geographical distances of the awareness. However, the defined data-centric approach can strengthen the awareness system by supplying necessary data from other remote entities in DNT to it, according to its current status and needs.

During data supplying of DNT, it is always very important to feed data to different services in an efficient and sufficient manner. The efficient data supply protects all data consumers from data-hungry status; the sufficient data supply ensures data provided to be reusable and be specifically targeting so that unnecessary/irrelevant data sharing is avoided. Thus, the SPSSE will reach a balance status that service needs are highly satisfied without being hungry for data or being over-fed of data, which is defined as *data equilibrium.*

However, for quite a long time, the discussions regarding IoT have been primarily focused on aspects of communication, networking, and hardware (Sheth, 2016)(Gubbi, Buyya, Marusic, & Palaniswami, 2013), while discussions regarding data and intelligence of IoT have been quite general and unspecific (Paper III). Especially, in much of the research, it is even hard to distinguish the differences between IoT and the conventional wireless sensor network (Paper III), as the discussions regarding IoT are primarily about the connected network devices for transmitting data to each other and the cloud.

To support SPSSE in the data-centric style, connection issues are hardly recognized as an obvious shortage for IoT according to the maturity level of the current communication technology(Martin Serrano, Elloumi, & Murdock, 2015). Furthermore, IoT issues that should be addressed are not simply about the communication, networking, and infrastructure. Semantic enhanced IoT as presented by the reports from the European research cluster on Internet of Things (Martín Serrano et al., 2015), the Alliance for Internet of Things Innovation (Martin Serrano et al., 2015), and (Knublauch, Fergerson, Noy, & Musen, 2004)(Sheth, 2016) lays basis for data-centric data supply in support of various services. Some researchers have provided IoT roadmaps of semantic interoperability to intelligently handle data and knowledge, but there is still a lack of applicable approaches targeting data supply in support of services (Henson, Sheth, & Thirunarayan, 2012)(Martin Serrano et al., 2015).

In order to fulfill the efficient data exploit in support of services, as described above, these essential issues need to be addressed:

The ability to perceive data, to perceive resources, and to perceive entity relations in dynamic environments should be enhanced, called perceptibility. It is important to make data supply targeted to fit the dynamic environments of the SPSSE into which it is immersed and to fit different service needs, as it is important to have efficient and sufficient data supply while handling the heterogeneity in distinct levels. To fulfill such data supply in data-centric style, IoT should perceive the resources and service needs in a uniform manner to establish mutual understandings for coordinating the distributed entities, which also adheres to the interoperability requirements toward IoT (Martín Serrano et al., 2015).

Resources should be coordinated to support the data supply in support of services. When exploiting the data of IoT, in many cases, it is very time-consuming and a waste of resources to send all data back and forth to the cloud for processing and then re-dispatching. It is useful to conduct some data exploiting work in the edge of IoT to optimize the data exploitation to assist the conventional cloud-based data handling approaches (Garcia Lopez et al., 2015). Such edge-assisted resource processing refines data before sending them to cloud to avoid unnecessary data traffic and data supply, which is also beneficial for data privacy by storing data in local nodes (Shi & Dustdar, 2016). Moreover, IoT entities, as important IoT resources, should be coordinated to collect data and accomplish service tasks, which should be based on the results of perceiving.

Environment dynamicity should be handled. Because SPSSE should suit the dynamically changing environments, data supplying should be enabled to understand the current environment status to further support the behavior of SPSSE, called contextualization (Paper IV), which further enables the SPSSE to respond and behave according to the pre-defined service policies and requirements based on the current environment status. Furthermore, the environment dynamicity leads to the need to make the data supply of IoT adaptive to the service policies for the SPSSE, which adaptively manages the relations between IoT entities (as the sources of IoT data) in dynamic environments. Based on that, the gap of perceptibility between different distributed IoT entities toward the dynamic environment can be handled for reaching data equilibrium, so that entities do not suffer from data-hungry or data-overfed.

Based on this analysis, it is not difficult to see the motivations and necessity to intelligently exploit the data of IoT by dealing with the three essential issues for strengthening IoT in data and knowledge aspects to support services. Therefore, this dissertation presents the method of data-centric network of things (DNT) to perceive, coordinate, and to supply data in support of services in data-intensive dynamic environments.

1.2 Research Problems

This section is to specify the problems adhering to the motivations. Specifically, the primary problem faced by IoT is how to intelligently exploit data (i.e., perceive, coordinate resources, and supply data) in the data-centric style to support various kinds of SPSSE with reaching data equilibrium. Furthermore, to intelligently exploit the heterogeneous data, the SPSSE should be able to interpret the heterogeneous resources and perceive the environments. Then, the system should be able to integrate data and coordinate resources between different entities for an efficient and sufficient data supply, reacting toward different types of dynamic environments. In responding to the primary problem, the three sub-problems are formulated as follows:

- Sub-problem I is to handle the heterogeneity of different entities and data objects of IoT regardless of their presences. IoT entities should not only refer to the objects with physical presences (e.g., devices) but also any kind of "thing" with or without a physical presence should be able to be constructed in IoT (e.g., web objects). Specifically, the physical entities refer to things such as sensors and actuators, while the entities without physical presences are virtual entities, which refer to things such as web objects, human as sensors, etc. Since entities in different components may be constructed in different ways by generating data of different content, it is difficult to establish mutual understanding between different IoT entities to conduct service tasks. Furthermore, data exploitation in IoT suffers from an ambiguity problem if the mechanism to handle heterogeneity is missing. Thus, methods are needed to bridge the gap of mutual understanding between the heterogeneous entities based on service needs, for instance.

- Sub-problem II is to coordinate the resources for data supply by following requirements, for example, by following the service needs perceived from the current environments. This is to enable IoT to interpret the environment status, based on which to react toward the current environments, which is called contextualization. Specifically, the scope of "contextualization" should not limit to the environments that end users are immersed into. The contextualization should also help SPSSE to monitor the service needs and requirements of different entities, thus the data can be supplied with data equilibrium.

- Sub-problem III is to handle the dynamic environments. Specifically, data exploitation and supply should be provided in an adaptable manner in response to the environment change. IoT is further expected to continually update data exploiting actions by learning from the environments based on adaptively managing the relations among entity.

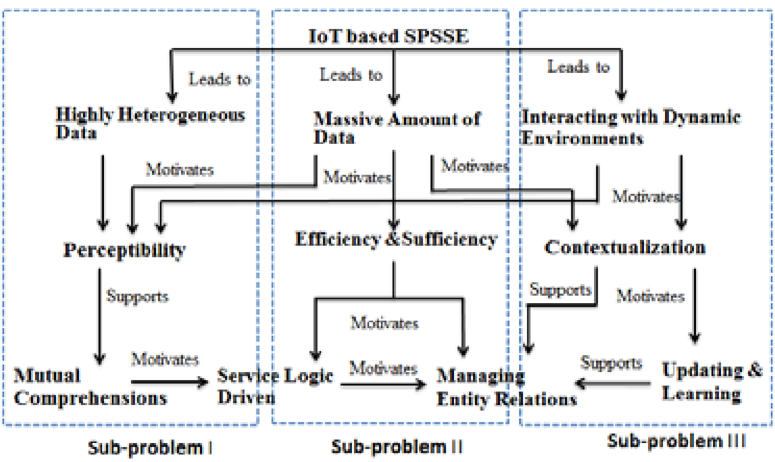

Figure 1: Problems and motivation map.

In connection with the analysis in section 1.1, the map is used to present the problems and to illustrate how the research is motivated, as shown in Figure 1. The problems intersect with each other, where perceptibility enhancement is mutually motivated by all the three problems. Additionally, in dynamic environments, managing entity relations is important for efficient and sufficient data supply.

1.3 Research Questions

The central research question for this thesis research is formulated as follows: *What are the methods of exploiting massive heterogeneous data of IoT with reaching data equilibrium to support various services?*

To answer this research question, it has been divided into the following sub-questions in responding to the problems illustrated in Figure 1. The sub-questions are defined as:

i. How can heterogeneity be handled in IoT?

In order to exploit the massive heterogeneous IoT data, heterogeneity is one of the essential issues should be handled. Heterogeneity challenges the data supply and resources coordination by hindering the commonly agreed perceiving of different IoT components. Specifically, handling heterogeneity indicates the requirements of perceptibility in following aspects: IoT requires a uniformed manner to understand these heterogeneous resources in a commonly-agreed way. Further, the IoT supporting SPSSE is required to understand the complex service sets and to conduct reasoning. Moreover, IoT needs to comprehend the context related to both the internal status of IoT and the external environments that IoT immersed into. Additionally, it should allow IoT to interpret the data, comprehend the needs of consumers, and then share the data correspondingly. Details regarding solving this research question will be discussed in Chapter 3.

ii. How can IoT resources be coordinated for data supplying?

Based on heterogeneity handling, the second essential issue is the process of coordinating resources for data supplying, specifically the criteria (e.g. time/money saving, etc.) that the process should obey further leads to the question regarding how to arrange IoT facilities to enable the data to be supplied that entities are not suffering from either data-hungry or data-overfed status. It further indicates the ability of IoT to arrange resources to retrieve and supply data to the relevant data consumers. In this case, a method should help to coordinate distributed entities to complete service tasks by cooperating within the same domain. Details regarding solving this research question will be discussed in Chapter 4.

iii. How can the dynamic environments be reacted toward?

The environments that SPSSE interacts with are changeable, which introduces the issue of dynamicity in which the data exploitation process should intelligently respond to the environments. Since the environments differ in type, data exploitation should be able to serve different types of environments. Reacting to dynamic environments further requires IoT to keep learning from the environments to update the data exploitation policy, which is used to deduce and derive reaction plans toward the current environment status, regardless of its type. The solution to this research question will be discussed in Chapter 5.

1.4 Research Methodology

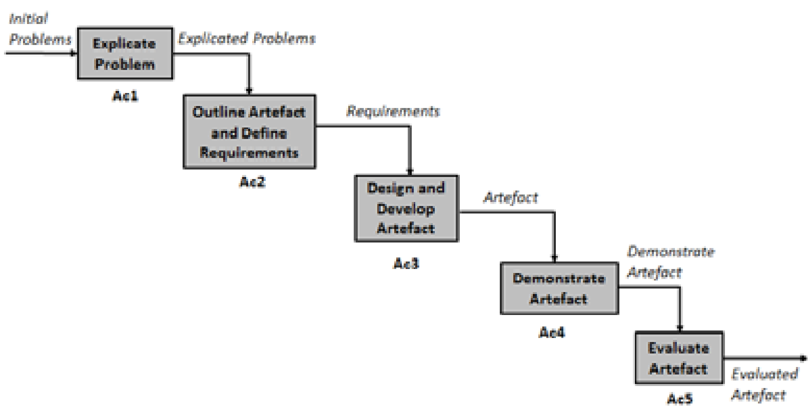

Figure 2: A design science research framework (Johannesson & Perjons, 2014).

The research is conducted based on the methodology of design science research (DSR), which is a paradigm of designing and developing new artifacts to solve problems and add new knowledge to science. Based on the DSR, a method of DNT is designed to solve the research questions (Section 1.3). Design science is an iterative process. Five activities are applied in the research with iterations, as shown in Figure 2, where each activity outputs an individual contribution to drive the research directly toward the final goal. This dissertation applies DSR framework briefly as follows:

- **Explicate the Problem**
  In Chapter 1, the research problems are articulated. The more specific problem analysis is conducted in Chapter 2. The discussions in Sections 1.1 and 1.2 specify the research area of this dissertation. The dis-

cussions in Chapter 2 summarize the relevant research in the research area by thoroughly analyzing the problems and existing limitations in the field. As the output of this activity, the research questions are clearly defined in Sections 1.1 and 1.2.

- **Outline the Artifact and Define Requirements**
  To solve the research problems and research questions, the research will design a method to deal with the defined problems by fulfilling certain requirements. Further addressing the explicated problem and research questions, the research will propose a solution based on the specific outline and requirements. Specifically, the solution should firstly enhance IoT perceptibility to handle the heterogeneity. Based on that, the method should enable IoT to coordinate and supply data to entities in data equilibrium status. Then, the method should enable handling the dynamic environments.

- **Design and Develop the Artifact**
  This dissertation presents a method, fulfilling the outlines and requirements output from the previous activity, to solve the defined research questions in Section 1.3. The designed artifact is a method that enables the conventional IoT to intelligently exploit a massive amount of heterogeneous data. The designed method includes both architectures and algorithms, which will be specifically presented in Chapters 3 through 5. Specifically, Chapter 3 will present answers to sub-question 1. Then, Chapter 4 will present answers to sub-question 2. After that, Chapter 5 will present answers to sub-question 3.

- **Demonstrate the Artifact**
  Chapters 3 through 5 will also specifically present how the designed methods can be applied in the problem area. Chapter 6 will also demonstrate the proposed methods via modeling, prototyping, and experiments. Based on the output of demonstration, the research moves to the final DSR activity to evaluate the artifact.

- **Evaluate the Artifact**
  The designed method is evaluated by how the defined problems are solved by the method (DNT). Moreover, what the designed method contributes to the d research area is presented.

1.5 Contributions

This dissertation proposes the method called the DNT to exploit massive heterogeneous data of IoT to support the IoT-based services, as compensation for the conventional IoT research which primarily focuses on problems of communication, network, and infrastructure. Specifically, this dissertation contributes knowledge to IoT and big data in the following aspects:

- **Logical and Dynamic Entity Interaction**

  The DNT realizes logical and dynamic interactions between entities to coordinate the entity resources (regardless of their presence) and intelligently exploits data with following the service logic (Paper I, II, VI), in reacting to the dynamic environments. Such logical and dynamic interaction between heterogeneous entities supports the coordination between IoT entities via entity mirror, which can enhance the interoperability between heterogeneous IoT entities (Paper I, II). Moreover, the presented research updates the entity relation sets by learning from the environments to respond to the dynamic environments (Paper II, V, VI).

- **Efficient and Sufficient Data Supplying**

  In responding to the vast heterogeneous data, the DNT utilizes the edge resources of IoT to comprehend the environment status and the needs of data consumers (Paper I, IV, V). Then, based on the comprehension, data can be supplied in a sufficient and efficient manner to avoid unnecessary and unexpected data traffic and sharing (Paper I, IV,) by following the service needs and by understanding the environment status. Moreover, perceptibility-enhanced data supply is proposed, which can support the interoperability between data and IoT entities (Paper I, IV, V).

- **Data-centric and Perceptual IoT**

  The DNT emphasizes enhancing the data and intelligence aspects of IoT (Paper I, V, VI). The efficient utilization of data in the data-centric style is helpful to release the incremental data pressure of IoT (Paper I, II, IV, V) by conducting data pre-processing. Moreover, data exploitation is enhanced with perceptibility so that data supply is accurately targeted to certain services based on understanding the needs (Paper II, V).

- **Support Services for Smart Digitalization**

  The DNT can support distinct kinds of services for smart digitalization, such as ambient intelligent services, smart vehicle services, and so on, by intelligently acquiring and supplying data to satisfy service needs in data equilibrium so that data consumers in SPSSE will not be in either data-hungry or data-overfed status (Paper I, IV, V). In addition, the edge-centric architecture is helpful for data privacy protection by reprocessing and storing some data locally before sending to the cloud (Paper II, IV), which is very important for various services.

1.6 Dissertation Structure

The organizational structure of this dissertation is shown in Figure 3, and the dissertation is formed under the framework of DSR. Chapters 1 and 2 carry out the work of DSR activities 1 and 2, respectively. Chapters 3 through 5 carry out the work of DSR activities 3 and 4, while Chapter 6 carries out the work of activity 5.

Chapter 1: 'Introduction' describes the research motivations, the research problems, the research questions, the methodology, and highlights the contributions. Specifically, DSR, as the research methodology applied in this dissertation, has been discussed.

Chapter 2: 'Related Work' summarizes the knowledge and limitations of the relevant work, which can further help motivate the research presented in this dissertation. The outlines and requirements toward the designed artifact are presented.

Chapter 3: 'Perceptibility Enhancement for Handling Heterogeneity' presents the perceptibility enhancement at different levels. Based on that, the heterogeneity can be handled for resource exploitation and to support various services. It answers the research sub-question 1.

Chapter 4: 'Smart Resource Coordination' presents the process to supply data in an efficient and sufficient manner based on smartly coordinating the resources. It answers the research sub-question 2.

Chapter 5: 'React Toward Dynamic Environments' will discuss the method to handle the dynamic environments. It answers the research sub-question 3.

Chapter 6: 'Evaluations' will discuss the evaluation of the methods in Chapters 3, 4, and 5 and evaluate the DNT.

Chapter 7: 'Conclusions' will conclude the dissertation by presenting an overview of the research problems and the corresponding research questions. The DNT method is briefly discussed, and the achievements of research are highlighted. The limitations of the research are discussed, which leads to suggestions for future work.

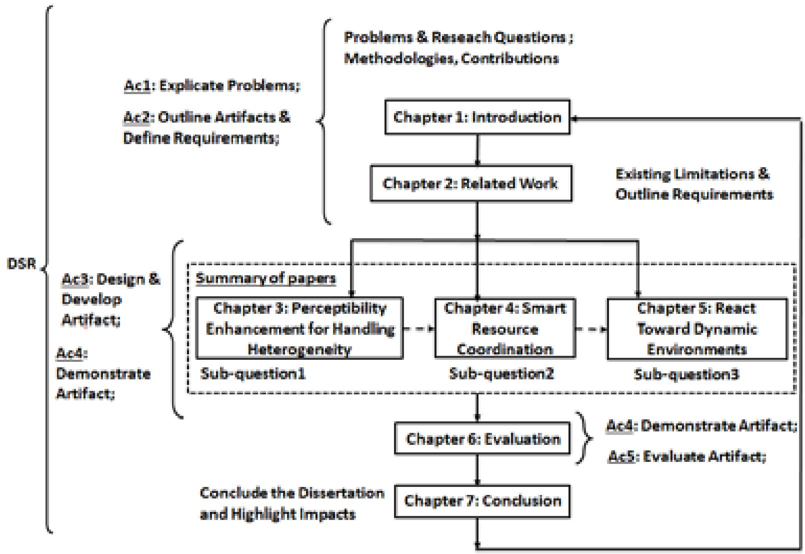

Figure 3: Dissertation road map.

1.7 Summary

This chapter first presented the motivation of conducting the research in this dissertation by summarizing the limits and the future expectations for the research area. Based on that, the author analyses the research problems and defines the research questions of this dissertation. Then, this chapter presents the DSR methodology that supports the research activities in this dissertation, explicating the organization of this dissertation. The contributions and effects of this dissertation are highlighted, and the structure of this dissertation is presented at the end.

2 Related Work

This chapter serves first to enrich the research background as described in the introduction and then to summarize the related concepts and work by presenting the limitations to stress the motivation for this research. Specifically, Section 2.1 will ground this dissertation in the research of IoT and big data. Sections 2.2 through 2.4 will summarize the related concepts and work and explain the essential and unaddressed issues that this dissertation is aimed to solve.

2.1 Limitations of Research on Internet of Things

The available research regarding IoT, for a long time, has been focused on connectivity issues; thus, the data and intelligence aspects of IoT have not been sufficiently emphasized. Recently, researchers have started to pay attention to the interoperability issues (Martín Serrano et al., 2015)(Martin Serrano et al., 2015)(Nambi, Sarkar, Prasad, & Rahim, 2014). However, an applicable framework and tools are still missing to exploit the data of IoT to support different services in data-intensive environments (Paper III).

2.1.1 Connectivity-centric network of things

For a long time, the research regarding IoT has been largely focused on the communication and physical platforms (e.g., cloud, wireless sensor network, and hardware) (Gubbi et al., 2013), while the data and especially the intelligence aspects of IoT data have not been emphasized enough (Lee & Lee, 2015)(Tsai, Lai, Chiang, & Yang, 2014). In addition, it is still a suspending issue regarding how to make the interaction between the heterogeneous entities interoperable (Martín Serrano et al., 2015). Because of these issues, it is hard to see the improvements of IoT compared to the conventional sensor network.

Specifically, conventional research has targeted different aspects regarding connectivity (Gubbi et al., 2013), for example, to provide efficient networking and communication channels to transmit data. However, in the near future, the connections and communications of IoT are highly unlikely to still be the limitations of IoT, according to the current level of networking technology (Martín Serrano et al., 2015)(Martin Serrano et al., 2015). Instead, with the increment data generated by IoT, it is an important topic to explore how to utilize these data, especially to support services (Paper III).

2.1.2 Interoperable network of things

Most recently, some research has started to stress the interoperability issue of IoT, such as (Palavalli et al., 2016)(Nambi et al., 2014); enhancing the interoperability of IoT has become an important issue (Martin Serrano et al., 2015), as it can support resource management and knowledge sharing for IoT. The interoperability (Paper V) of IoT refers to the ability to set up common understandings between different IoT modules to handle heterogeneity, which relies on semantic annotations, reasoning and mining for data aggregation, and dynamic and flexible architecture. At the technical level, the interoperability of IoT involves mutual interoperability between IoT entities, interoperability between IoT entities and resources, and interoperability between IoT entities and system status.

However, based on the blueprint of a semantic interoperable IoT, there are many issues remaining to be solved (Martín Serrano et al., 2015)(Martin Serrano et al., 2015). Among those, three issues have significantly become essential. The first issue is to enable interpretable data sharing and knowledge retrieving, resource organizing, and knowledge provision. Further, that raises the needs for a set of methods to organize data and resources in a perceptive way for knowledge support. Based on that, it should support perceptive data sharing to fulfill certain parameters and satisfy certain requirements.

2.1.3. Over-cloud issue of IoT

For a long time, the cloud has taken the primary role of maintaining and processing data for distributed systems because of the ideal volume and efficiency of cloud services (Lee & Lee, 2015)(Gubbi et al., 2013). However, in IoT, over-depending on utilizing cloud services for data management also brings some issues. For example, blindly sending data back and forth between the cloud and end devices can cause unnecessary costs on time and traffic. It also could raise suspicions regarding data privacy protection (Garcia Lopez et al., 2015)(Shi & Dustdar, 2016). Specifically, if it lacks a pre-filtering and integrating mechanism before sending data to the cloud, the incremental amount of IoT data will make data more complex and difficult to exploit.

In IoT, not all the data should be handled by the cloud. The edge components of IoT can become an efficient compensation of the cloud for exploiting data (Garcia Lopez et al., 2015)(Shi & Dustdar, 2016). The edge of IoT plays a promising role in recognizing the needs and status of data consumers and to conduct data pre-filtering and interaction to refine the information stored in the cloud (Garcia Lopez et al., 2015). In addition, when storing some data on the edge, the end data consumers take responsibility for maintaining the data. That is beneficial to decrease the suspicion toward data privacy (Shi & Dustdar, 2016).

2.2 Constrained Data Support for Various Services

Besides issues like connectivity and overuse of the cloud, IoT is still facing the following problems, which hinder its support for various services.

2.2.1 Static data transmissions

As discussed in Section 2.1, conventional research regarding IoT focuses on communications between IoT entities. IoT primarily shares and distributes data between the entities without knowing what the data mean or to what the data are related, and data sharing is conducted based on the pre-designed static channels. Such static and physical data sharing brings problems in two aspects. First, continuing to retrieve and process data in a static manner in such a blind way challenges the data supply efficiency with the increasing data. Second, making the useless/irrelevant data travel back and forth between end devices and the cloud can cause unnecessary resource consumption. Many end devices can be organized to form a resource pool on the edge side of IoT, where IoT can conduct pre-processing of the data to improve the efficiency of resource utilization.

To enhance IoT with data and knowledge processing ability, there is a strong need to set up a dynamic mechanism in which data exchange can be conducted in a dynamic way (called entity interaction) by considering the change of the data consumer's needs and the environment status. Moreover, in compensation for the data transmission between IoT physical objects, the entity interaction should present interactions between both virtual things (without physical presences, e.g., web objects) and physical things (with physical presences, e.g., sensors.). In addition, the data exchange between heterogeneous entities is driven by service needs and is triggered by environment changes.

2.2.2 Constrained environment perceptibility

The perceptibility enables entities to establish common mutual understanding by comprehending the environment status, which is an efficient method to recognize the needs for exploiting IoT data. However, the existing research toward IoT has quite limited definitions regarding what should be comprehended from the environments IoT immersed into. For the SPSSE established upon IoT, they utilize the distributed sensors to monitor the environment status. For example, in a smart home, sensors are deployed to monitor the safety status to enhance the behavior of slightly dementia people (Paper II). Based on that, services are provided in response to the user behaviors and changing environments. In this case, such descriptive information retrieved by IoT is usually called context (Bellavista, Corradi, Fanelli, & Foschini, 2012)(Perera, Member, Zaslavsky, Christen, & Georgakopoulos, 2014). Further, such context, indicating the user status and user-immersed environments (called environment-centric context), usually supports the cognitive intelligence for various smart ubiquitous services (e.g., ambient assisted living, smart urban, etc.). However, in considering supporting services in different domains, the descriptive information should not be limited to only the user status and surrounding environments. Thus, the context can also refer to the self-descriptive information to describe the internal system, which is used to make SPSSE become self-adaptable based on perceiving, such as the autonomous sensor network (Modukuri, Hariri, Chalfoun, & Yousif, 2015). The context indicating the self-description information of the system (called system-centric context) are usually applied to internal intelligence services, such as autonomous networks (Ranganai et al., 2014) and autonomous sensor networks (Modukuri et al., 2015)(Marzencki, Huang, & Kaminska, 2011).

These two different types of context information are usually presenting the different smart types of IoT with a gap between each other. The environment-centric contextualization takes data and device resources of IoT to support reasoning and mining; in this case, IoT itself has not been enabled with intelligence yet. However, many researchers refer to such cases as the intelligence of IoT, which does not make IoT smart. Instead, enabling the intelligence of IoT should, for example, make IoT self-adaptable based on system-centric contextualization, thus intelligently exploiting its massive resources. In addition, utilizing both the environment-centric and system-centric contextualization can enable IoT to intelligently support services for other system modules of SPSSE based on supporting efficient resource exploitation.

2.2.3 Constrained entity relations computations

Until recently, the entity relation computation approaches could be generally categorized as using a quantity-driven approach or logic-driven approach. Ontology-based IoT resource annotation, as one of the commonly accepted logic-driven methods to construct the semantic smartness for IoT (Strang & Linnhoff-Popien, 2004), is a formalization process based on utilizing logic to make the annotated IoT objects machine understandable. The logic-driven approaches utilize logic-based deduction based on formalizations to describe, comprehend, and discover the relations between entities. The quantity-driven approaches utilize mathematical relations and probabilistic models to describe and discover the quantity relationships between entities represented by the datasets generated by the entities. In this case, data-driven intelligence methods, such as Markov models (Lau & Tham, 2012) and neural networks (Bowman, Potts, & Manning, 2015), are usually used.

In recent years, the quantity-driven intelligence methods have been widely discussed and have attracted a lot of attention, specifically deep learning (Deng & Yu, 2013), Markov decision process (Gast, Gaujal, & Le Boudec, 2012), temporal difference learning (Tesauro, 1995), etc. They have been applied to support different intelligent services (e.g., behavior monitoring). As an advantage, such quantity-driven approaches enable the SPSSE to learn entity relations from the collected data and hence to give recommendations and predictions for new relations and make the system reactions smart without pre-programming. However, compared to the logic-driven approach, such methods show weakness regarding comprehending and reasoning for complex policy sets and logic-based reasoning. In addition, such quantity-driven methods are sensitive, and depending on the collected data for training, in many cases, the shortage of data samples would be a problem in practice.

For some services, especially those handling complex service rules or policies (e.g., handling traffic rules for smart urban services (Zanella, Bui, Castellani, Vangelista, & Zorzi, 2014) and the autonomous network (Ranganai et al., 2014)), logic-driven approaches are still a very practical choice to interpret the rules, reasoning, and execution of the rules. However, the logic-driven approach primarily conducts reasoning based on the existing knowledge base, which is limited to learning from the environmental data in contrast to the quantity-driven approach.

Thus, to strengthen IoT to exploit data, it is important to both enable IoT to interpret logics but also to refresh the knowledge base by learning from the environments. The DNT will utilize the hybrid framework of both the quantity-driven and logic-driven approaches to strengthen IoT.

2.3 Summary

This chapter firstly discussed the research background to ground the research of this dissertation. In addition, it summarized the existing research backgrounds and existing limitations of the related work from two aspects, namely, the limited perspectives regarding IoT and the constraints of data support for services, to highlight the motivations again. Chapters 3 through 5 will present the DNT by summarizing the included research papers.

3 Perceptibility Enhancement for Handling Heterogeneity

Targeting the research questions defined in Chapter 1 and the problems stated in Chapter 2, this chapter presents the collection of the author's research to enhance the perceptibility toward the massive resources and dynamic environments. For the DNT, the perceptibility enhancement helps IoT handle the heterogeneity. The rest of this chapter will present three sections, which will present perceptibility enhancement at various levels for heterogeneity handling.

3.1 Analyzing the Heterogeneity

IoT entities producing and consuming data regardless of the presence are categorized into different roles according to how they act toward the data (Paper II). Based on the coordination between entities, different services are provided in response to the service policies (i.e., service logics). By retrieving data from and making a response to the dynamic environments, the SPSSE refreshes the knowledge base to evolve toward the environments. The heterogeneity for IoT comprises four levels, as shown in Figure 4, namely, the data level, entity level, service level, and knowledge level.

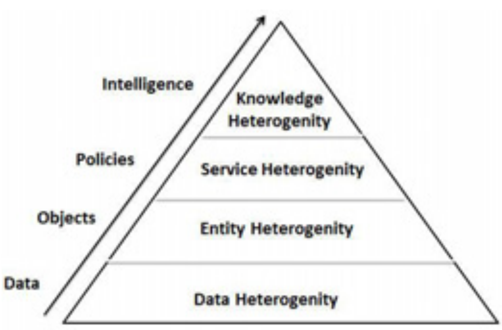

Figure 4: Heterogeneity for the data-centric network of things.

- Data-level heterogeneity: As discussed in the introduction, since the data generated by IoT differs in format and content, it causes heterogeneity at the data level.
- Entity-level heterogeneity: The "things" for IoT are not limited to objects with physical presence (e.g., brokers, sensors, etc.) because some objects contribute data to IoT through virtual presence (e.g., web objects, social media characters, etc.). With the heterogeneous presence, entities differ in performance and actions in responding to different service needs and lack mutual understandings toward each other. This causes heterogeneity at the entity level.
- Service-level heterogeneity: As IoT-based SPSSE are highly distributed, different system modules usually provide services in response to the local situation instead of in a global sense. Usually, different modules lack mutual understanding toward the services needs and status of each other, which makes it difficult for global coordination. That causes heterogeneity at the service level.
- Knowledge-level heterogeneity: By interacting with the dynamic environment, IoT generates and maintains a knowledge base to adjust data-sharing relations. During the entity's interaction, the knowledge base is continually refreshed by adding knowledge learned from new environments, which challenges the integration between the new knowledge base and old knowledge base, which causes heterogeneity at the knowledge level.

To support IoT for efficient data exploitation, heterogeneity is handled layer-wise. Specifically, Section 3.2 will summarize the heterogeneity handling in the data and entity layers. Section 3.3 will summarize the heterogeneity handling in the service layer, and Section 3.4 will summarize the heterogeneity handling in the knowledge layer.

3.2 Constructing Perceptible Data Objects and Entities

As discussed, entities generate data in heterogeneous content and format, which makes the data heterogeneous. In addition, the generated data present the current status of environments, which can lead to the change of the relations between entities based on mutually perceiving. Thus, the heterogeneity of data and heterogeneity of entities mutually affect each other. Therefore, resolving the data heterogeneity is tightly connected with resolving the entity heterogeneity.

Specifically, on one hand, formalizing the data objects using semantics to provide a machine-understandable formality can strengthen the perceptibility of IoT to handle heterogeneity. On the other hand, machine-learning models to recognize relations between data objects in the sense of entities' relations based on the initialized ontology model can also strengthen the perceptibility of IoT to handle heterogeneity. The former is a logic-driven approach that bridges the gap between the data and entity behavior; the latter is a quantity-driven approach that enhances quantitative relation recognition.

In the semantic-based approach, the data objects are constructed using the framework of ontology engineering, which is an important way to represent knowledge. The ontology framework should be proposed by the designer according to their service scenarios. Using this method, the properties of the data objects can be structured, as shown in Figure 5, to make the data objects support logic-based reasoning.

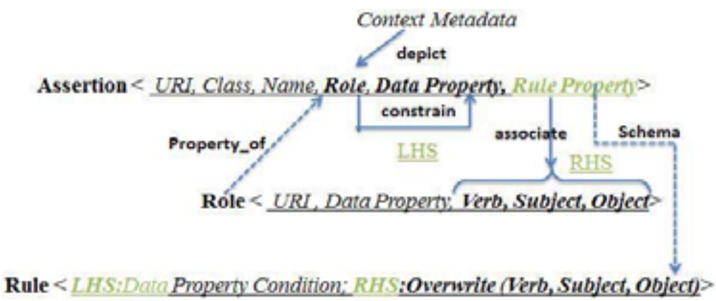

Figure 5: The structural property of data objects (Paper I).

Besides the semantic-based enhancement for data objects, the quantitative approach conducts data relation mining on the data objects generated by the entities on the edge side of IoT. Thus, the semantic relations between IoT entities represented by the current relations between data objects can be recognized (Paper V), which hence can handle the heterogeneity of data by strengthening perceptibility. Adhering to the ontology-based structure in the description of the relations between data objects generated by entities, deep recursive architecture is then applied to the relational learning based on the proposed ontology framework, as presented in Figure 6. The data flowing from the lower layer to the upper layer is a process of data integration and quantity-based formalization, by which the virtual entities can be constructed as required in the semantic model. In the conducted research (Paper V), an auto-encoder has been used for data retrieval and integration.

On one hand, the relations between entities are represented by the relations between the data objects generated by the entities, considering the relations between data suppliers and data consumers. On the other hand, the relations between entities are driven by the need to accomplish a certain task.

To let the SPSSE perceive the roles of entities in cooperation to conduct certain tasks, the entity mirror is introduced. Targeting the heterogeneity at the entity level, the entity mirror helps the SPSSE perceive the service relations between both virtual and physical entities.

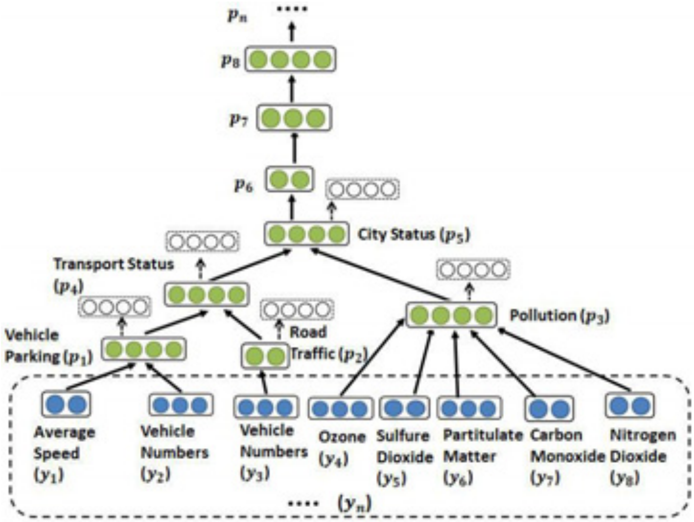

Figure 6: The relation recognizer (Paper V).

The entity mirror is an object-based mapping from the physical world to virtual world, where the virtual world is a logic-based service field organizing and coordinating all the relevant resources. The method creates a mirror for each entity to semantically present the status of heterogeneous entities from the physical world to the virtual world, reflecting the service logics and attributes of each entity. The mirror presents the attributes and behavior of the entities in responding to their physical presences (particularly the physical entities). The data of the attributes of the entity mirrors are retrieved from physical sensor devices, and the behavior of the entity mirrors are performed by the actuator devices. Using this method, the physical entities can be constructed by several coordinated distributed physical objects, without the limitations of its physical presence. The entity mirror is semantically annotated and driven by the defined service logics, which further makes the relations between entities logic-presentable and can be deduced. Figure 7 describes the model for an entity mirror.

To form the entity mirror, four sessions in five steps are taken, as presented in Figure 8. The first session is to construct a collective platform where the distributed physical objects can be smoothly connected in a dynamic and flexible way with smooth connections. In the second session, the semantic annotation is conducted to the data objects generated by the entities. In the third session, the entities are associated with each other and driven by logics and service requirements. Based on the support from previous sessions, the fourth session bridges the gap between entities and services, with the resolved heterogeneity in previous sessions.

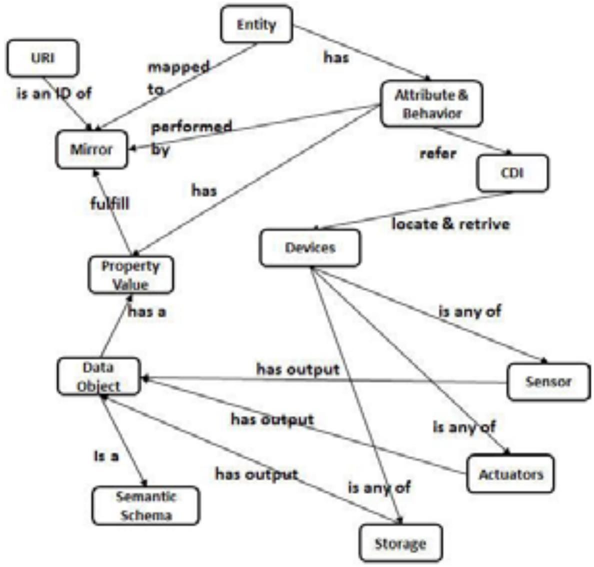

Figure 7: The model of entity mirror (Paper II).

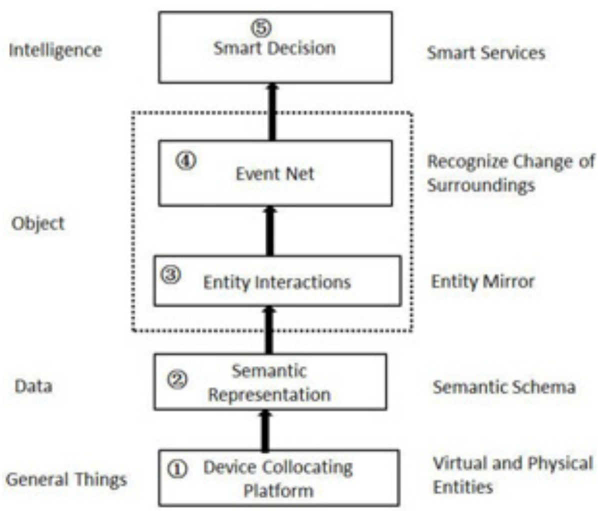

Figure 8: The sessions for constructing the entity mirror (Paper II).

3.3 The Perceptible Services

As discussed in Section 3.1, the heterogeneity at the service level is caused by the different modules conducting activities according to their own local situations. In this case, service logics can be introduced to enhance the perceptibility of the activities in the global view and to coordinate different modules to accomplish a task and thus to handle heterogeneity at the service level.

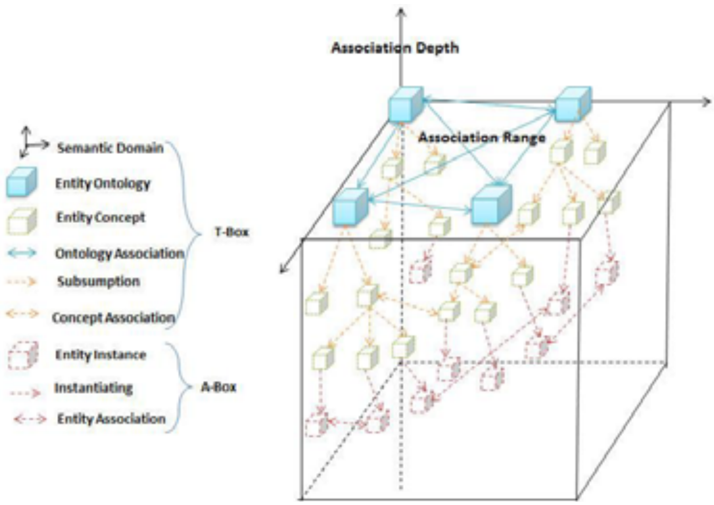

Figure 9: The semantic space based on service logics (Paper V).

Service logics are machine-understandable formalized rules, which are in the presentation of service requirements (Paper II). The semantic enhancement for these rules is a formalization process based on ontology engineering, based on which, the SPSSE can conduct reasoning on the knowledge base using the defined service logics. Specifically, the service logics are constructed using both inner service logics and external service logics. Internal service logics set up deduction based on direct interactions with the ontology, which represent service requirements and basic knowledge in this service domain. Based on the framework of inner service logics, external service logics represent additional service rules for the presented object-oriented entity mirrors. By that, service logics can support the SPSSE to coordinate modules by forming a space for reasoning, as shown in Figure 9. Technically, the service logics can be depicted using rule-based language, such as Jess (Friedman-hill, 2003).

Service logics comprise the essential basis to deal with heterogeneity at the service level and to coordinate the services between both virtual and physical entities. Different from the heterogeneity at the entity level, which emphasizes the inner factors of entities, the heterogeneity between entity modules emphasize cooperating and resource sharing between the modules to finish the same tasks. A module of an entity is a cluster consisting of IoT entities that obey the same service logics and share the same semantic domain. Further, the clustered entities can be coordinated to form a virtual entity despite the physical distances, as presented in Figure 10.

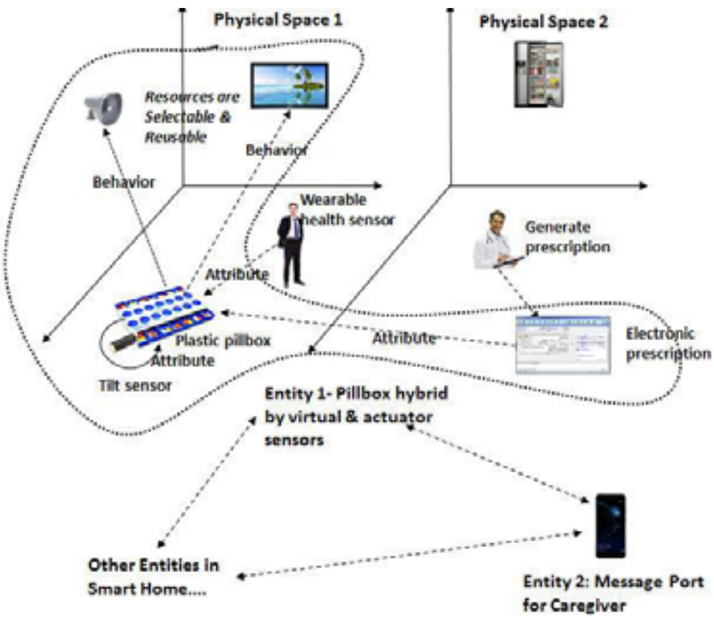

Figure 10: Constructing a virtual pillbox (A sample module of entities) (Paper II).

3.4 Environment Perceiving and Knowledge Updating

As discussed in Section 3.1, the heterogeneity at the knowledge level is primarily caused by the difference between the old knowledge base and the new knowledge base retrieved from the environments. The knowledge base supports the perceptibility of different service. In many cases, it can describe the entity relations. To handle the knowledge-level heterogeneity, the DNT should be contextualized to perceive environments and to discover new relations between entities and to update the existing knowledge base.

Enhancing the perceptibility at the data and entity levels lays the basis for the contextualization. The perceiving toward context information includes two aspects: on one hand, the contextual data are interpreted under the framework of service logics, which is a logic-driven deduction process; on another hand, the contextual data can be mined using models like the machine-learning model, which is helpful to discover the potential relations and update knowledge by such quantity-driven processes.

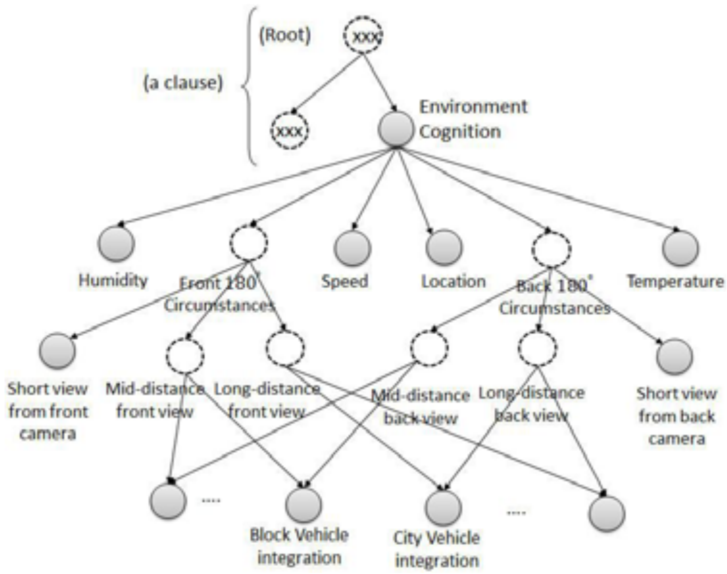

Figure 11: Updating the existing knowledge (Paper VI).

Specifically, contextualization allows SPSSE to acquire the ability to understand the environments for adapting its behavior. Different from the conventional contextualization, which primarily targets the perceiving of user-immersed environments, the contextualization presented in this dissertation includes the external and internal contextualization. External contextualization enables SPSSE to comprehend the external environments for adaptability. Inner contextualization enables the SPSSE to perceive the change of its inner status, which establishes an adaptive loop inside the system. The hybrid utilization of external and internal contextualization should depend on specific smart service scenarios.

Based on the contextualization, newly discovered relations will be added to the existing knowledge base, while adhering to the service logic framework. Specifically, SPSSE will add new nodes to the existing knowledge network describing entity relations based on the subsumption relationship. For example, the node "short view from back camera" can be added to the existing knowledge using a relation recognizer. The deep recurve models presented in Figure 11 can support data mining under the logic-based framework.

3.5 Summary

This chapter summarized the collection of research, which presented how the perceptibility can be enhanced to handle the heterogeneity at various levels. That lays the basis for efficient data exploitation. Based on the perceptibility enhancement for handling heterogeneity as discussed in this chapter, the next chapter will discuss data supply for DNT.

4 Smart Resource Coordination

As discussed in Chapter 3, based on the perceptibility enhancement for handling heterogeneity at various levels, the DNT is able to comprehend data, service needs, and environments. The perceiving allows the SPSSE to establish understanding toward both internal and external contexts. Based on that, DNT coordinates resources to supply data in support of various services. Further, this requires that resource sharing between distributed entities is based upon perceiving. Furthermore, it indicates the data sharing between distributed entities to be coordinated in an interoperable manner, which is very important to intelligently exploit IoT data. Based on that, the data supply can protect services from either data-hungry or data-overfed status, and service intelligence can be enhanced by data integrated from distributed nodes.

4.1 Edge-based Data Processing

As discussed in Chapter 2, IoT is facing an over-cloud issue in which a substantial amount of data have been sent back and forth between the edge and cloud, during which the cloud has been overused for data processing. The problem introduced by the over-cloud issue is not because it over-stresses the cloud platform. Instead, it is because, for time-sensitive services, sending data back and forth to the cloud for processing takes extra time. In addition, for privacy-sensitive services, managing data in local edge devices is helpful for trust enhancement. The vast heterogeneous data generated by IoT are very close to the edge devices. In addition, edge devices can provide a considerably large resource pool for data processing, by organizing the entities in a distributed but highly coordinated manner. Using the edge resource pool, edge-based data processing can be conducted before sending the data to the cloud to lighten traffic pressure.

To organize the edge entities in a distributed but highly coordinated manner, an architecture in a hybrid of the centralized and decentralized structure is introduced (Paper IV). With that architecture, the computing task can be carried out by the distributed entities under the coordination of the mediating entities, as presented in Figure 12. Specifically, there are two layers in the presented hybrid architecture as shown in Figure 12. The first layer is constructed of highly coordinated but distributed mediating entities that organize a semantic domain, within which the end devices (e.g., a smartphone) can share and exchange data according to the same service target. In this layer, entities are organized in a totally decentralized manner based on a distributed hash routing (Maymounkov & Mazi, 2002) method, by which to avoid a static central point. In addition, in this layer, mediating entities can freely join and leave a semantic domain according to the requirements. In the second layer, the far edge side entities can propagate the data by pushing them to the mediating entities and receiving data from the meditating entities in a publish/subscribe pattern. In addition, in the second layer, entities are organized in a highly dynamic and flexible centralized mode in which the mediator conducts semantic-based data processing by receiving data from the edge entities, but the edge entities still can freely join and leave the hosting of a certain mediating entity.

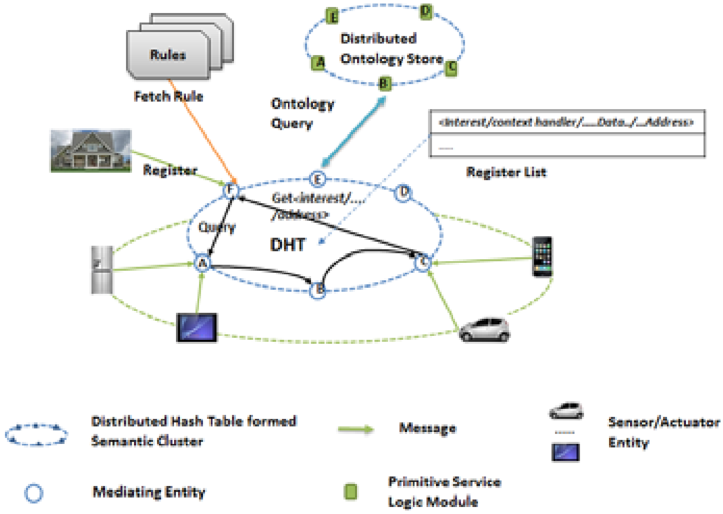

Figure 12: The edge-based data processing (Paper IV).

4.2 Resource Coordination for Distributing Data

Data should be efficiently supplied to the entities, namely, to share and exchange between entities based on the perceiving results. That further raises the need to set up a mechanism for dispatching data to match the semantic reasoning, which is called distributing data.

Based on the perceiving result, the technique for distributing data, such as the semantic-based publish/subscribe, is introduced as one promising solution in the application layer of DNT. In the semantic-based publish/subscribe, the subscribers deliver and continually update contextual annotations to the mediator entities where the contextual annotations describe the interests and status, which can be deduced by logic. The data sent out by the publisher to the mediator will then be processed based on the annotations to match the available semantic domain using logic reasoning and hence to match the subscribers. Both publisher and subscriber can reside on the same edge entity so that each edge entity would be able to both receive and deliver data with other entities. Figure 13 presents the semantic-based publish/subscribe.

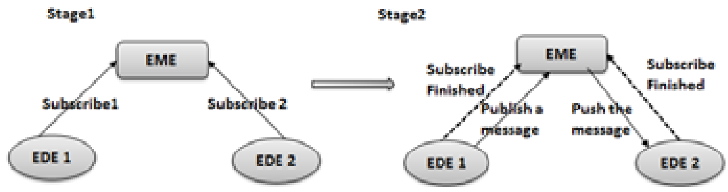

Figure 13: The semantic-based publish/subscribe (Paper IV).

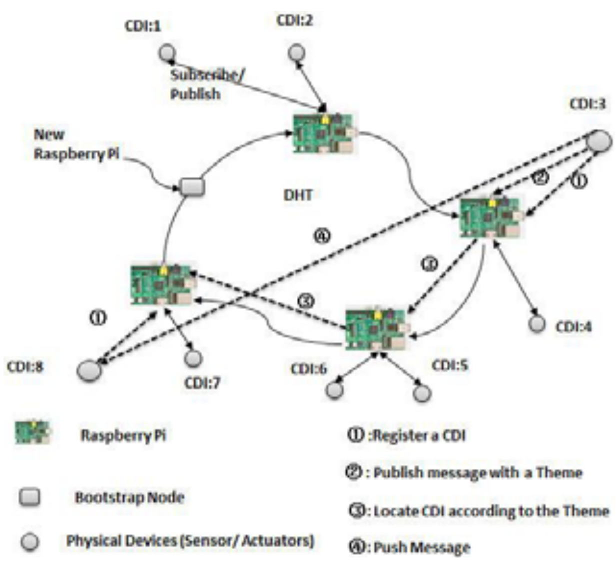

Figure 14: The device collocating platform (Paper II).

Data supply, namely, data sharing and exchanging based on semantic cognition supports the computing tasks of services. However, to implement the perceiving results, the entity resources also need to be coordinated and provided in response to the service needs based on the interoperability enhancement discussed in Chapter 3. To support the coordination of entity resources (e.g. devices), the logical interaction (Paper II) mechanism is needed, which will establish a platform to organize the devices in an object-oriented manner. Specifically, based on the created entity mirrors presented in Chapter 3, the platform maps the physical world to the virtual world by managing the behavior and attributes of the objects. The functionalities of entity attributes are then fulfilled by input devices, such as sensors, and the functionalities of behaviors are then fulfilled by the output devices, such as actuators. The entity resource coordination and management under the framework of service logics is based on the support of the device collocating platform, as presented in Figure 14.

In considering the changing Internet protocol (IP) address of the entities, for example, the same mobile device can have different Internet access points, the platform should provide a uniform entity label in the application layer independent from the IP address of the devices. Specifically, each device will be allocated with an individual identifier associated with the IP address. The identifier and IP address pair is stored in the virtual storage formed by the distributed hash table (DHT) (Needels & Kwon, 2009). Each device takes responsibility to update their IP addresses and identifiers, and virtual storage is constructed by the devices registered in the DHT table. Thus, the platform can manage and utilize device resources in a distributed and flexible manner.

4.3 Resource Coordination for Knowledge Enrichment

The data perceiving by static sensors embedded in the physical environments is always limited by the physical distances. As an improvement to such embedded sensing, the pervasive sensing technology allows to acquire data from distributed environments. As an improvement for the pervasive sensing technologies, the DNT enriches the knowledge of different IoT modules via perceiving and efficient data sharing between entities in a coordinated manner. The data exchange between entities and modules is based on the perceiving toward service needs and environment status to ensure data equilibrium. Using this way, DNT lays the basis for the entities to acquire relevant knowledge from the entity formed networks. Thus, each entity in the network can enrich knowledge without the limitations of hardware and geographical limitations, so that the solo-island of knowledge can be avoided by perceiving in this coordinated manner.

Such knowledge enrichment based on perceiving in the coordinated manner can support services in many scenarios. For example, as presented in Figure 15, in conventional advanced driving assistance systems (ADAS), the vehicles perceive the environments via embedded sensors (such as radio, camera, laser, etc.). However, such methods depend on physical sensors bringing some blind areas for sensing, so that the recognition ability and recognition scope are challenged by obstacles and physical distances, as the recognition ability of one or several sensors is always limited. Specifically, vehicles have difficulty with detection if the obstacles are hidden around corners. In addition, such rough and blind data sharing is very difficult for the system to efficiently get the needed information. Not limited to traffic status detection, future smart vehicles should be able to acquire information regarding, for example, currently available parking spots and driver needs from remote users to optimize the driving plan. The formed DNT can help change the conventional standalone recognition to a knowledge network with perceiving in the coordinated manner.

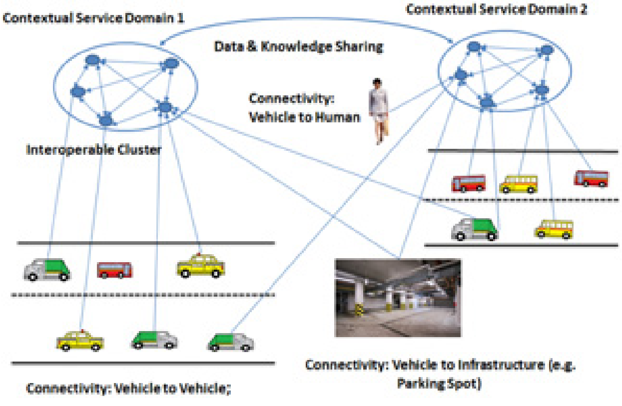

Figure 15: A scenario of knowledge enrichment--perceiving in the coordinated manner.

4.4 Summary

This chapter discussed the coordination of resources for data supply in support of services, based on enhanced perceptibility. Supported by perceiving in the coordinated manner, it forms a network of knowledge to improve the recognition ability and scope, which can support services in many domains, such as the services of smart vehicle.

5 React Toward Dynamic Environments

Chapter 4 presented resource coordination for SPSSE to efficiently acquire and supply data based on perceived results. As the environments in which IoT-based SPSSE are immersed are highly dynamic, which makes the entity relations vary from time to time. In addition, with the changing of environments, sometimes the existing knowledge regarding entity relations is hard to suit the current environment status. All these factors make the resource supply very dependent on the current status of the environments. Thus, the resource sharing and exchanging between entities must dynamically adapt to the current environments to learn from current environments to update knowledge regarding entity relations.

5.1 Knowledge-based Self-adaptation

DNT supplies data based on the relations between entities, which keep changing over time. That further requires an enabler to manage and update the entity relations to maintain the consistency between entity relations and the environments. This enabler should help DNT to form a loop, in which it can perceive the data collected from edge devices and output perceiving results, can learn from the environments and output new knowledge to enrich the current entity relation sets, and can support data supply based on current entity relation set. Thus, the DNT can form an autonomy loop in the data-centric style for evolving the entity relation sets with learning from the environments (as presented in Figure 16 (Paper VI)). Based on that, the data supply becomes self-adaptable to the environments.

There are many available methods to create an autonomous loop, such as (Ray, 2013)(Liu & Jia, 2012)(Peters, Ketter, Saar-Tsechansky, & Collins, 2013)(Katasonov & Terziyan, 2009). However, none of them have clearly presented the methods to update and maintain entity relations. Different from other self-adaptation methods, in order to handle the dynamic entity relation sets of DNT in the data-centric style, the self-adaptation method for DNT must be able to both interpret the service logics and process the environment data, and be able to spontaneously evolve the entity relation set by learning from environment data. Thus, it can make the data supply react toward the dynamic environments. Such an autonomy loop emphasizes on responding to the dynamic environments by maintaining and updating the entity relation sets, which specifically supports the services of logic-intensive and data-intensive SPSSE (e.g., autonomous network (Ranganai et al., 2014) and smart urban systems(Nikolaos, Nikolas, Ioannis, & Dimitrios, 2016)).

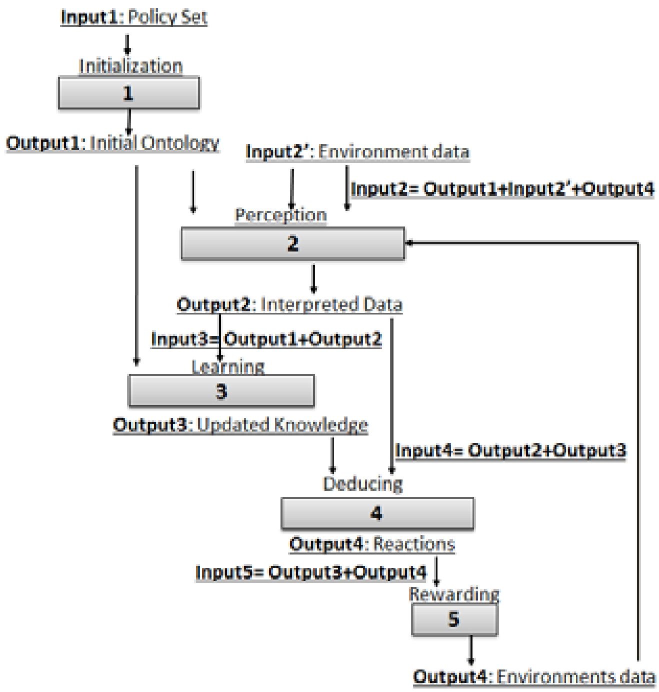

Figure 16: The autonomous loop for managing entity relations (Paper VI).

5.2 Entity Relation Evolvement

The self-adaptation of DNT creates an entity relation network using ontology models. There are different methods for the ontology model of IoT nodes, such as the semantic sensor network (Compton et al., 2012). Besides that, a subsumption-based model (Paper V) is helpful for data integration between entities as well, as shown in Figure 17. Nodes E to J present physical devices and some virtual entities that generate data, while Nodes A to D represent virtual devices. In the model presented in Figure 17, data relations from the bottom layer to the top layer are in a process of information integration, with the reflection of the relations between entities. The model in the described structure forms a tree in which the path starting from leaves to the root reflects the process of data integration between entities. Hence, the entity relation detection can start from its root node.

Different from relevant models, the presented model in Figure 17 encapsulates entities in heterogeneous presence by managing the entity relations based on the data supplying and consuming relations between entities. In addition, the ontology-based entity relation model is helpful to make a bridge between the entity relation sets with the service logics and an event net, as shown in Figure 18. The event net enables the DNT to respond to the dynamic events of the environments.

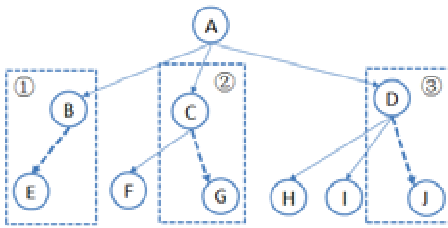

Figure 17: Knowledge updating.

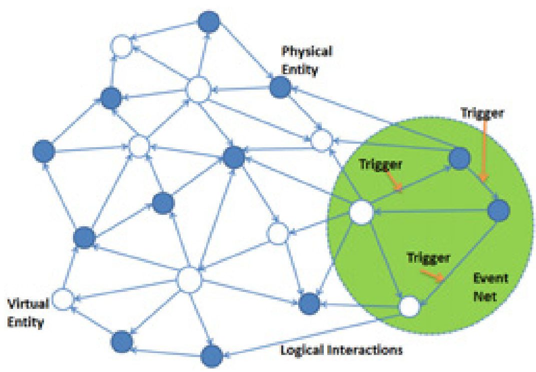

Figure 18: The event net based on entity relations (Paper II).

As discussed, using the presented autonomous knowledge updating loop, the DNT can conduct self-evolvement toward the dynamic environments by enriching and updating the existing knowledge base regarding entity relations. The updating loop is based on the reasoning integrated with learning. In the DNT supported SPSSE, reasoning is conducted by logic-based deduction on the current knowledge base (Paper II).

To interact with the dynamic environments in a flexible manner, the SPSSE should be enabled to spontaneously learn new relations from the collected data, which can use, for example, machine-learning techniques (Paper VI). Specifically, the learning procedure keeps adding new nodes to the existing knowledge base from the perceived environment data, by recognizing and learning the relations between knowledge nodes, as presented in Figure 17. The new Nodes E, G, and J are retrieved from the environments, which will be added to the existing model for updating. During that process, the deep recursive neural network (Paper V, VI) can be applied for relation recognition to locate and add new nodes; the relation recognition is conducted in ①, ②, and ③ for knowledge enhancement.

5.3 Summary

Based on the interoperable resource sharing based on the perceiving, as presented in Chapters 3 and 4, this chapter concludes the research, which handles the dynamicity of environments. Based on an ontology model and by conducting self-evolvement via learning from the environments, the DNT can spontaneously adjust the entity relations for data supply in a flexible manner.

6 Evaluations

The previous three chapters have presented DNT. As the artifact extracted from the authors' research to intelligently exploit massive amount of heterogeneous data in support of services, the evaluations and verifications for DNT spread in each included publication. This chapter summarizes the approaches conducted in the research to verify the DNT and the results. As presented in the previous chapters, the DNT includes both architectures and algorithms. Specifically, the algorithms include the logic-based algorithms and quantity-based algorithms. The coming sections will present the approaches to evaluate the architecture and algorithms of presented works and the results.

6.1. Approaches for the Verification of Architectures

The evaluation of architecture aims to verify whether the proposed architecture can achieve correct functionality and proper performance. In this dissertation, model checking and prototyping have been used to verify the proposed architecture.

The model checking is to verify the conceptual design. As discussed in Chapters 3 through 5, DNT uses an architecture hybrid of distributed structure and centralized structure for data sharing and exchanging, and the entities resources are also coordinated under the same architecture for accomplishing the outputted tasks of SPSSE. In such highly distributed resource coordinating and data dispatching network, each entity and module are running in different functionalities and roles, which cannot be ignored. Additionally, the relations between entities are changing over time due to the dynamic environments. Thus, the model for architecture checking needs to easily represent the DNT using finite states and to easily express model properties. Also, the model should make it easy to describe the components of DNT and their behavior (Garlan, Khersonsky, & Kim, 2003). In responding to the aspects discussed above, the timed automata (Yovine, 2005) is used to describe DNT for model checking. Even though the specific properties for checking architecture of DNT may slightly vary for different SPSSEs, it is still necessary to check some basic properties (e.g., deadlocks, reachability, etc.). In addition, model checking can verify that the system can be guaranteed to arrive some the expected status by fulfilling some conditions (Paper IV), for example, a message is always delivered if there are entities matches with it.

The prototyping verification is to quickly implement and run the modules with essential functionalities, to check the system performances under various conditions. For example, the mediators and the entities interacting with the mediators can be prototyped to verify the essential functional correctness and performance by monitoring the data processing and dispatching (Paper II, IV) between them.

The evaluation methods discussed above have been applied to the research in each included research paper. As the evaluation of the hybrid architecture of DNT, model checking based on timed automata is conducted in Paper V. As the results, it is proved to work correctly in logic with some properties are satisfied, for example, a message can always be delivered to the entity if there is a match between them. As the evaluations of entity resource coordination, the entities' interactions and the data dissemination are verified by prototyping in Paper III and Paper V. As the results, they both deliver correct functionality with acceptable performances. Thus the proposed architecture is correct both in theory and in practice to supply data by reaching the expected status and properties.

6.2. Approaches for the Verification of Algorithms

The algorithm verification aims to check the correctness and accuracy of the algorithms for DNT. Particularly, the algorithms of DNT include both the logic-based and quantity-based algorithms, which need to be verified differently.

The logic-based algorithms are primarily to handle service logics and semantics in which the ontology and logic have been processed (Paper I, II). Even though it may slightly vary by different SPSSs, parameters like consistency, satisfiability, and instantiation can be checked through the proposed service logics and ontology when specific basic knowledge basis is given. Reasoning engines (e.g., Jana (Mcbride, 2002), Jess(Eriksson, 2003), etc.) are used to realize the checking.

As quantity-driven algorithms, the artificial neural network models are used to calculate the relations between entities, for which the verification takes accuracy and loss as primary parameters to check. Specifically, tools such as the *K*-folder cross-validation (Kohavi, 1995) are used to evaluate the performance of the machine learning algorithms. In addition, the conditional probabilistic calculation is used to detect the systematic reliability by receiving the reliability different from each component.

The evaluation methods discussed above have been applied to the research in each included research paper. As the evaluation of the semantic data constructing and service logic processing, the described verification approach for logic-based algorithms is conducted in Paper I and Paper II. As the results, they both deliver logically correct results. As the evaluation of the data integration and entity relation management, the described verification approaches for quantity-driven algorithms are conducted in Paper IV and Paper VI. As results, they all provide acceptable accuracy to support the functionality DNT. Such verification confirms the correctness of the proposed algorithms and ensures acceptable performance of them.

6.3 Summary

This chapter summarized the evaluation approaches applied to the authors' research included in the dissertation. The discussed evaluation approaches have been applied individually in each included publication in which the evaluation for each research procedure of the DNT is specifically conducted.

7 Conclusions

The previous chapters proposed and demonstrated the DNT to efficiently exploit the massive heterogeneous data of IoT in data-centric style to support various services. This Chapter serves to summarize the research, highlight the achievements, and discuss the future work.

7.1 Summary of Achievements

In responding to answer the primary research question formulated in section 1.3, this dissertation proposes a method called DNT to answer the three sub-questions derived from the primary research question. The DNT exploits massive heterogeneous data to support various IoT-based services in dynamic environments using the data-centric style, which has achieved in following three aspects:

i. DNT enhance perceptibility, based on which to handle heterogeneity at the data level, entity level, service level, and knowledge level, as discussed in Chapter 3. The semantic-based perceiving technology is proposed to enable IoT to comprehend service logics (Paper I and Paper II), and entity relations (Paper II). Such perceptibility enhancement enables DNT to handle heterogeneity in distinct level to support data supplying. Thus, the sub-question *i* has been answered.

ii. Based on the perceptibility enhancement, DNT utilizes a hybrid architecture in the edge side of IoT to coordinate resources to support data supplying as discussed in Chapter 4. The resource coordination is based on service logics (Paper I and Paper II) and is adaptable to the service needs for data supplying (Paper IV), which also helps to accomplish the service tasks of SPSSE (Paper II) in the coordinated manner. Thus, the sub-question *ii* has been answered.

iii. DNT manages dynamic relation among entities (Paper I and Paper V) to support data supplying (Paper IV). As an enhancement to the semantic-based perceiving toward entity relations, deep learning techniques are utilized to integrate data (Paper V) under the semantic framework (Paper I) and to update the entity relations by learning from the data collected from dynamic environments (Paper VI). Thus, the sub-question *iii* has been answered.

Not limiting to the achievements discussed above, DNT additionally brings following positive effects:

i. Exploiting data to support various services**:** The DNT enhances perceptibility of IoT to comprehend service needs and dynamic environment to supply data in data-centric style, as discussed in Chapter 3, 4 and 5. In addition, the presented DNT reacts to the dynamic environments with self-adaptability (Paper IV) and self-updating (Paper VI). Thus, The DNT supports various services by supplying data to avoid either data-hunger status or data-overfed status, which is quite important for services (Paper III) in the digital age.

ii. Relieving big data pressure of IoT: The DNT utilizes and coordinates resources in IoT edge in the first-time manner to supply data according to service needs and environment status, as discussed in Chapter 3, 4 and 5. This helps release the incremental data pressure by preprocessing (Paper III) data to avoid unnecessary data sharing (Paper IV, Paper IV), thus to avoid unnecessary resource cost and to help relieve data pressure in some degree (Paper III).

7.2 Future Work

While DNT has achievements discussed above, there are still several open issues that shall be addressed in the future, in relation to the discussed essential aspects:

i. Adding artificial intelligence computing (i.e. machine learning and semantic reasoning) to enhance data supplying of IoT unavoidably introduces extra time costs. Thus, time performance enhancement is needed to minimize the caused extra processing time in support of time-critical services.

ii. The gap between semantic reasoning and learning still exists due to the existing gap between logic-based intelligence and quantity-based intelligence. Integration solutions are needed. Thus, reasoning and learning can be seamlessly integrated for knowledge updating in support of services in highly accurate manner. This is important for the services which cannot get rid of regulations of complex rules and for the services facing the pressure of massive amount of data.

In the future, it is meaningful to solve the two issues described above. Moreover, it is also meaningful to realize and implement the DNT to support various services for smart digitalization (e.g. smart vehicles, smart manufacturing, smart urban, smart healthcare, etc.).

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Part II

Included Publications