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**The Research Grants Council of Hong Kong
NSFC/RGC Joint Research Scheme
Completion Report**

(Please attach a copy of the completion report submitted to the NSFC
by the Mainland partner)

Part A: The Project and Investigator(s)

1. Project Title

Searching and Browsing Cyber-Physical Objects

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator (<i>with title</i>)	Professor Jiannong Cao	Professor Minyi Guo
Post	Chair Professor	Chair Professor and Head
Unit / Department / Institution	Department of Computing, The Hong Kong Polytechnic University	Department of Computer Science and Engineering, Shanghai Jiaotong University
Co-investigator(s) (<i>with title</i>)	Dr Dan Wang Associate Professor	Dr Jingyu Zhou Assistant Professor

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval (<i>must be quoted</i>)
Project Start date	1 January 2013		
Project Completion date	31 December 2016		
Duration (<i>in month</i>)	48		
Deadline for submission of Joint Completion Report	31 December 2017		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Investigate the applications and their requirements, and identify the challenging issues on search and browsing of cyber-physical objects;
2. Model the cyber-physical objects and their contextual relationships;
3. Design a framework including system architecture and major functional components, with networking and computing mechanisms, algorithms, and middleware support, for finding, storing and searching the information about cyber-physical objects;
4. Develop techniques for the construction and maintenance of the contextual relationships between cyber-physical objects and design the user interface for browsing and navigating the objects following the contextual links;
5. Develop a system test-bed and software prototypes with example applications and demonstrations.

5.2 Revised Objectives

N/A

6. Research Outcome

6.1 Major findings and research outcome

(maximum 1 page; please make reference to Part C where necessary)

Our research outcome generated from this project is fruitful, including ten journal papers and eight conference papers. The majority of our research outcome has been published at top conferences like IEEE International Conference on Pervasive Computing and Communications (PerCom) and IEEE International Conference on Distributed Computing Systems (ICDCS), and top journals like IEEE Transaction (TII), IEEE Transaction on Services Computing (TSC) and IEEE Intelligent Systems (IS).

We proposed the concept of UIO and formally defined it in [J2017d] as a uniform model for modeling smart devices and their relationships. Based on the UIO model, we have developed easy-to-use tools to facilitate creation of virtual devices, environments, and scenarios. The study of UIO not only makes the development of cyber-physical objects easier but also enable a wide range of applications in various areas like mobile computing and wireless sensor networks.

According to different themes, our research outcome can be categorized into three sectors: **Smart objects as UIOs, UIO relationships, and Applications based on UIO.**

Smart objects as UIOs

Smartphone is a typical UIO. With the repaid development, the privacy issues of smartphones are becoming urgent and important. We proposed systems to understand users' privacy expectations in various mobile apps and help them to mitigate privacy risks accordingly using crowdsourcing [C2015a, C2016a, J2016c]. Besides, we addressed the requirement of building local social networks using smartphones in [C2017d]. One special feature of our work is that it does not rely on Internet connection. We leverage the Wi-Fi tethering technique, and let ones' smartphone to switch between Wi-Fi hotspot mode and Wi-Fi client mode to exchange information with nearby people.

We also studied other smart objects like vehicles and smart cushions. In [C2015b], we proposed a novel connectivity-oriented data dissemination algorithm to maximize the network connectivity probability in vehicular Internet access networks based on probabilistic analysis. We devised a smart cushion to recognize fine-grained sitting posture in a low-cost and non-intrusive way [C2017a]. The cushion incorporates very thin pressure sensors to offer nonintrusive experience, an effective sensor placement solution to reduce cost, a set of user-invariant features and an ensemble learning classifier to improve generalization ability.

UIO relationships

To coordinate and interact with each other, UIOs are usually associated with certain relationships. We systematically investigated human social relations and published a survey paper on social context-aware middleware [J2015a]. A software architecture containing main services provided by a social context-aware middleware is proposed in our survey. Based on the architecture, we summarized and classified existing works. At the conclusion of the survey, we pointed out open challenges, e.g. data heterogeneity, efficient context recognition and privacy, for future directions. Discovery of the relationship between smart objects is also a critical and nontrivial task in cyber-physical

integrated network applications. We build a distributed system model and propose an efficient relationship-discovery algorithm for cyber-physical networks to support different types of applications [J2015c], aiming to find the most stable relationship in the heterogeneous and dynamic cyber-physical network.

Once UIOs are connected, a fundamental requirement is to search for specific UIOs according to their various relationships. In [J2016a] we formalize the probabilistic time-constrained path (PTP) query over uncertain road networks which is proved NP-hard. To answer PTP queries efficiently, we propose an efficient approach with effective pruning strategies and the probabilistic/rank requirements of queries. We also addressed the energy efficiency problem and proposed an active tag searching algorithm in large scale RFID systems [J2015b]. The proposed searching protocol in Multiple reader RFID systems pushes per tag energy consumption to the limit as each tag needs to exchange only one-bit data with the reader.

Applications based on UIO

The UIO model enables a wide range of applications in various areas like crowdsourcing, mobile computing and wireless sensor networks.

For crowdsourcing, we modelled human as UIO and studied how to them to effectively complete crowdsourcing tasks and propose a long-term dynamic quality-aware incentive mechanism for crowdsourcing in [C2017c]. The proposed framework takes full advantage of workers' historical information and predicts their quality accurately for quality inference and parameters learning.

For mobile computing, we successfully solved RFID tag size profiling (TSP) problem in multiple reader RFID systems [C2017b] and passive RFID reader localization problem [J2014] based on the proposed UIO model. In [C2017b], we proposed a time-efficient algorithm that uses two heuristics to quickly find enough linearly independent equations for the linear system to solve the TSP problem. In [J2014], we proposed an effective fault-tolerant RFID reader localization approach that can handle regional permanent fault, and provide quality measurement of localization results. We also proposed a cluster based scheduling approach for integrating multiple programming systems to relieve the burden of common users of conducting data processing tasks [C2016b]. The proposed approach helps in minimizing the make span of workflows and resource consumption. Last, we studied the problem of room level localization of mobile devices and proposed a novel solution to solve the challenge caused by similar wireless fingerprints. We managed to combine the radio frequency feature and room feature to significantly improve the localization accuracy [C2015c].

For wireless sensor network, we implemented an in-network processing paradigm combining two efficient heuristics in domain-specific monitoring applications [J2017b]. The proposed algorithm successfully evades inefficiency and ineffectiveness caused by traditional way of collecting and processing data in a central node. Besides, we also developed several interesting and practical applications. In [J2016b], a solution of scheduling mobile sensors and fixed sensors for target tracking is proposed based on a realistic detection model. We also use a data-driven approach to study the impact of human beings on wireless coverage. The proposed solution can not only estimate potential dead spots of an on-site access point deployment but also quantifies their severity, using

simple Wi-Fi data collected from the on-site deployment and shop profiles from the Internet. Lastly, we proposed a middleware for wireless sensor network based structure health monitoring applications using the service-oriented architecture (SOA). SOA uses loosely coupled services that can be reused flexibly to develop different applications [J2017a].

All of the proposed systems have been carefully evaluated in different test-beds. Our researchers have given related keynotes in many conferences and workshops like IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks (WoWMoM 2017) and The International Conference on Orange Technologies (ICOT 2017). We also demonstrated some works in many international conferences like ACM CHI Conference on Human Factors in Computing Systems (CHI 2014), and Conference on Ubiquitous Intelligence and Computing (UIC 2015) (UIC Best Video Award) which are highly recognized by the community. Some works have demo videos online, e.g. like smart cushion. (<https://www.youtube.com/watch?v=aoJpMfhwNPo&feature=youtu.be>).

6.2 Potential for further development of the research and the proposed course of action (*maximum half a page*)

There remain many challenging problems for cyber-physical integration and management, at both the object and system level. These problems include how to further develop the abstractions and algorithms for smart objects and their interactions in large scale heterogeneous and dynamic environments like IoT systems, how to discover and manage contextual relationships with big data increasingly available, and how to explore the functionalities of UIOs for various kinds of applications. Our works in this project build models and provides foundations to address the above issues.

7. **The Layman's Summary**

(*describe in layman's language the nature, significance and value of the research project, in no more than 200 words*)

In this project, based on the popular IoT concept we devise a more general term, cyber-physical object or Ubiquitous Intelligent Object (UIO), which integrates places and human beings. UIO refers to any physical object that has a cyber-identity.

We firstly conduct comprehensive literature review to specify motivation, requirement, and challenging issues of this project. Then we highlight two main themes under this project and identify quite a lot insightful and challenging problems.

The first theme emphasizes human as UIO. With the rapid development of technology, human beings can be regarded as an intelligent object using their smartphones as proxies. Under this emerging trend, we addressed privacy issues of smartphones, effective interaction with other type of UIOs and published papers in many top international conferences like PerCom and ICDCS.

The second theme focus on UIO network. Since an efficient and effective network is foundation of many services, like searching for and tracking an UIO. We have proposed two search algorithms addressing energy issue and dynamic issue of UIO network. We also made contribution in effective network processing. Our research outcome has been published on top conferences like INFOCOM and top journals like TII and TSC.

Part C: Research Output to date

- 8. Peer-reviewed journal publication(s) arising directly from this research project** (please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge funding support from this scheme by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) (<i>bold the authors belonging to the project teams and denote the corresponding author with an asterisk*</i>)	Title and Journal/ Book (with the volume, pages and other necessary publishing details specified)	Submitted to RGC (indicate the year ending of the relevant progress report)	Attached to this report (Yes or No)	Acknowledged the support of this Joint Research Scheme (Yes or No)	Accessible from the institutional repository (Yes or No)
Year of publication	Year of Acceptance (For paper accepted but not yet published)	Under Review	Under Preparation (optional)						
2014				Weiping Zhu*, Jiannong Cao , Yi Xu, Lei Yang, and Junjun Kong	Fault-Tolerant RFID Reader Localization Based on Passive RFID Tags, <i>IEEE Transactions on Parallel and Distributed Systems (TPDS)</i> 25.8 (2014): 2065-2076. [J2014]	No	Yes	Yes	Yes
2015				Guanqing Liang*, Jiannong Cao	“Social Context-Aware Middleware: A Survey”, <i>Pervasive and Mobile Computing Journal (PMCI)</i> . 17(B): 207-219 (February 2015). [J2015a]	Yes, 2014	Yes	Yes	Yes
2015				Shigeng Zhang*, Xuan Liu, Jianxin Wang, Jiannong Cao , Geyong Min	“Energy-Efficient Active Tag Searching in Large Scale RFID Systems”, <i>Information Sciences</i> . 317: 143-156 (October 2015). [J2015b]	Yes, 2014	Yes	Yes	Yes
2015				Hongliang Lu*, Jiannong Cao , Weiping Zhu, Xianlong Jiao, Shaohe Lv, and Xiaodong Wang	“DMRUT-MCDS: Discovery Relationships in the Cyber-Physical Integrated Network”, <i>Journal of Communications and networks</i> . 17(6): 558-567 (December 2015) [J2015c]	No	Yes	Yes	Yes
2016				Wengen Li*, Jihong Guan, Xiang Lian, Shuigeng Zhou, Jiannong Cao	“Probabilistic Time-Constrained Paths Search over Uncertain Road Networks”, <i>IEEE Transactions on Services Computing (TSC)</i> . PP(99): 1 (June 2016). [J2016a]	No	Yes	Yes	Yes

The Latest Status of Publications				Author(s) (<i>bold the authors belonging to the project teams and denote the corresponding author with an asterisk*</i>)	Title and Journal/ Book (<i>with the volume, pages and other necessary publishing details specified</i>)	Submitted to RGC (<i>indicate the year ending of the relevant progress report</i>)	Attached to this report (<i>Yes or No</i>)	Acknowledged the support of this Joint Research Scheme (<i>Yes or No</i>)	Accessible from the institutional repository (<i>Yes or No</i>)
Year of publication	Year of Acceptance (<i>For paper accepted but not yet published</i>)	Under Review	Under Preparation (<i>optional</i>)						
2016				Tian Wang*, Zhen Peng, Junbin Liang, Sheng Wen, MD Zakirul Alam Bhuiyan, Yiqiao Cai, Jiannong Cao	“Following Targets for Mobile Tracking in Wireless Sensor Networks”, <i>ACM Transactions on Sensor Networks (TOSN)</i> . 12(4): 31:1-31:24 (September 2016). [J2016b]	No	Yes	Yes	Yes
2016				Rui Liu*, Jiannong Cao , Kehuan Zhang, Wenyu Gao, Lei Yang, Junbin Liang, Ruiyun Yu	“Understanding Mobile Users’ Privacy Expectations: A Recommendation-based Method through Crowdsourcing”, <i>IEEE Transactions on Services Computing (TSC)</i> . PP(99): 1 (December 2016). [J2016c]	No	Yes	Yes	Yes
2017				Yuvraj Sahni*, Jiannong Cao , Xuefeng Liu	“MidSHM: A Middleware for WSN-based SHM Application using Service-Oriented Architecture”, <i>The Elsevier Journal of Future Generation Computer Systems (FGCS)</i> . (January 2017). [J2017a]	No	Yes	Yes	Yes
2017				Peng Guo*, Jiannong Cao , Xuefeng Liu	“Lossless In-network Processing in WSNs for Domain-specific Monitoring Applications”, <i>IEEE Transactions on Industrial Informatics (TII)</i> . PP(99): 1 (April 2017). [J2017b]	No	Yes	Yes	Yes
2017				Jiaying Shen*, Jiannong Cao , Xuefeng Liu, Chisheng Zhang	“DMAD: Data-Driven Measuring of Wi-Fi Access Point Deployment”, to appear in <i>ACM Transactions on Intelligent Systems and Technology (TIST)</i> . (2017). [J2017c]	No	Yes	Yes	No
	2017			Rui Liu*, Junbin Liang, Jiannong Cao , Weiping Zhu, Sebastian VanSyckel, and Christian Becker	“UIO-based Testbed Augmentation for Simulating Cyber-Physical Systems”, to appear in <i>IEEE Intelligent Systems</i> (2017). [J2017d]	No	Yes	Yes	No

9. Recognized International conference(s) in which paper(s) related to this research project was/were delivered (please attach a copy of each delivered paper.)

Month/Year/ Place	Title	Conference Name	Submitted to RGC (indicate the year ending of the relevant progress report)	Attached to this report (Yes or No)	Acknowledged the support of this Joint Research Scheme (Yes or No)	Accessible from the institutional repository (Yes or No)
June/2015/New York, USA	PriWe: Recommendation for Privacy Settings of Mobile Apps based on Crowdsourced Users' Expectations [C2015a]	IEEE Mobile Services 2015 (IEEE MS 2015)	No	Yes	Yes	Yes
October/2015/Dallas, USA	CoDA: Connectivity-Oriented Data Dissemination Algorithm for Vehicular Communication Networks [C2015b]	11 th International Conference on Mobile Ad-hoc and Sensor Networks (IEEE MASS 2015)	No	Yes	Yes	Yes
April/2015/Hong Kong, China	Feature-Based Room-Level Localization of Unmodified Smartphones [C2015c]	International Workshop on Smart Cities and Urban Informatics (SmartCity 2015)	No	Yes	Yes	Yes
March/2016/Sydney, Australia	PriMe: Human-centric Privacy Measurement based on User Preferences towards Data Sharing in Mobile Participatory Sensing Systems [C2016a]	IEEE International Conference on Pervasive Computing and Communications (IEEE PERCOM 2016)	No	Yes	Yes	Yes
July/2016/Fuzhou, China	A Cluster Based Approach for Task Scheduling across Multiple Programming Systems [C2016b]	15 th International Symposium on Parallel and Distributed Computing (IEEE ISPDC 2016)	No	Yes	Yes	Yes
March/2017/ Kona, Big Island, Hawaii, USA	Smart Cushion: A Practical System for Fine-grained Sitting Posture Recognition [C2017a]	2 nd IEEE PerCom Workshop on Pervasive Health Technologies (PerHealth 2017) (in conjunction with IEEE PerCom 2017 - IEEE International Conference on Pervasive Computing and Communications)	No	Yes	Yes	Yes
May/2017/ Atlanta, GA, USA	Tag Size Profiling in Multiple Reader RFID Systems [C2017b]	IEEE International Conference on Computer Communications (IEEE INFOCOM 2017)	No	Yes	Yes	Yes
June/2017/Atlanta, GA, USA	MeLoDy: A Long-term Dynamic Quality-aware Incentive Mechanism for Crowdsourcing [C2017c]	37 th IEEE International Conference on Distributed Computing Systems (IEEE ICDCS 2017)	No	Yes	Yes	Yes
June/2017/Macau, China	Wi-Friend: Identifying Potential Real Life Friends Nearby [C2017d]	IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks (IEEE WoWMoM 2017)	No	Yes	Yes	Yes

10. Student(s) trained (*Please attach a copy of the title page of the thesis.*)

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
WANG Yuqi	PhD	14 August 2014	To be graduated in around July 2018

11. Other impact (*e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.*)

N/A