| RGC Ref.: PolyU505/12 |
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| *(please insert ref. above)* |

# The Research Grants Council of Hong Kong
# ANR/RGC Joint Research Scheme
# Completion Report

*(Please attach a copy of the completion report submitted to the ANR by the French researcher)*

## Part A: The Project and Investigator(s)

### 1. Project Title (ANR Acronym)

Coordination and Computation in Distributed Intelligent MEMS (CO2Dim)

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

| | Hong Kong Team | French Team | French Team |
|---|---|---|---|
| Name of Principal Investigator *(with title)* | Professor Jiannong Cao | Professor Julien Bourgeois | Professor Michel Raynal |
| Post | Chair Professor and Head of Department | Professor and Head of Department | Professor |
| Unit / Department / Institution | Department of Computing, The Hong Kong Polytechnic University | Department of Computer Science, University of Franche-Comté | University of Rennes |
| Contact Information | csjcao@polyu.edu.hk | Julien.Bourgeois@univ-fcomte.fr | raynal@irisa.fr |
| Co-investigator(s) *(with title and institution)* | Dr Alvin Toong Shoon Chan (Singapore Institute of Technology) [*Ex-Co-I of HK Team*] | Dr Eugen Dedu and Dr Hakim Mabed (University of Franche-Comté) | |

### 3. Project Duration

| | Original | Revised | Date of RGC/ Institution Approval *( must be quoted)* |
|---|---|---|---|
| Project Start date | 1 March 2013 | | |
| Project Completion date | 29 Feb 2016 | 31 Aug 2016 | 27 Aug 2015 |
| Duration *(in month)* | 36 | 42 | 27 Aug 2015 |
| Deadline for Submission of Completion Report | 31 Aug 2017 | | |

## Part B: The Completion Report

### 5. Project Objectives

5.1 Objectives as per original application

The objectives of the project range from theoretical study to implementation of software and hardware testbeds.

1. Study and survey literature on the design issues of a real-time programming language for DiMEMS (Distributed Intelligent MEMS).
2. Design and implement a real-time programming model and language library for DiMEMS.
3. Develop a reliable runtime system for the programming model to support program execution with timing constraints.
4. Develop application programming interfaces for fault detection and fault-tolerance support in the system.
5. Design and implement different testbeds: e.g. a simulator, a hardware in the loop testbed and a fully integrated testbed.

5.2 Revised Objectives

N/A

## 6. Research Outcome

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, mainly including one book chapter, five journal papers, and four conference papers. Meanwhile, a realistic multi-robot system has been developed. The system has been demonstrated in many international conferences and exhibitions, and our publications have received international recognition from the distributed computing community.

We did a comprehensive literature review about programming language for DiMEMS. Based on the literature review, we proposed a real-time development framework towards programming DiMEMS. The proposed framework is composed

of three layers: real-time programming model layer, compilation layer and runtime system layer. We investigated the design challenges and requirements in these layers and discussed future research directions [J2016b]. We also investigated two prototypes of DiMEMS, namely multi-robot system (MRS) and wireless sensor network (WSN). For the MRS part, we described the essential requirements and applications of MRS, did a comprehensive taxonomy of existing middleware for the multi-robot system by analyzing their features, and surveyed over 14 different middleware for MRS [B2016]. For the WSN part, we conducted an exhaustive investigation on WSN-based structural health monitoring (SHM) applications with an emphasis on networking perspectives and propose a taxonomy of SHM techniques and their applicability to WSNs [J2017]. These surveys are significant for other researchers and us towards developing DiMEMS systems and applications.

We proposed and designed a new programming model called RMR to control large-scale multi-robot system. RMR is a logic programming model, which enables programmers to focus on high-level application requirements of "what to do" and leave low-level implementations (e.g., data management and communication) of "how to do" to the runtime system. Moreover, it allows developers to specify timing constraints on the behaviors of the robots, such as setting deadlines and identifying the time orders of actions. To support distributed execution of RMR programs, a compiler and a runtime system are developed for RMR. The compiler is able to convert the RMR programs into executable byte-codes, and then distribute the byte-codes to each robot. The runtime system is responsible for interpreting and executing the bytecodes. To evaluate the performance of RMR, we deployed RMR in a simulator and a realistic testbed, and then developed several example applications [C2016].

We proposed several fundamental algorithms for purposes of detecting fault [J2016a], saving energy [J2015] and cardinality estimation [C2017a]. These algorithms can also be used in other areas and other applications. In specific, [J2016a] is a predicate detection algorithm which can be used in general asynchronous distributed system. Since fault can be regarded as a special case of predicate in distributed systems, the proposed predicate detection algorithm can be used for detecting fault. [J2015] serves as an efficient algorithm for multi-hop broadcast in a low-duty-cycle wireless sensor network. We proved it is NP-hard to find the optimal solution for the energy saving problem and designed an approximation algorithm that can achieve a polylogarithmic approximation ratio. In [C2017a], the proposed algorithm for cardinality estimation can be used to estimate the number of MEMS units in DiMEMS.

We developed a test-bed of distributed multi-robot system as the prototype of DiMEMS. The testbed includes eight robots and a localization system. The robots are designed by our laboratory and are equipped with a wireless communication unit and various sensors. The localization system can achieve centimeter level accuracy of localization for the robots. Based on the distributed multi-robot system, we evaluate the proposed programming model and distributed algorithms. Demo including "multiple robots pass through corridor" and "multiple robots form different shapes" are developed upon the system. To achieve the demos, we proposed a uniform circle

formation algorithm for the multi-robot system, which can be used in the application of area coverage and exploration [C2017b].

We also apply DiMEMS technology in the field of Medical Cyber-Physical-Systems (MCPS). Traditional MCPS have limited capabilities to detect human errors because of only integrating medical devices, and thus, often result in late device coordination when patients are found to have already developed significant adverse physiological reactions. We successfully build context-aware MCPS to avoid such risky situations [J2014], [C2014].

Besides the impactful publications, we also presented our prototype DiMRS in various international conferences and exhibitions. Several keynote speeches were conducted at international conferences such as CWSN 2016, ISPDC 2016, and APAC Innovation Summit on Robotics 2016. The developed multi-robot system was also exhibited in many international exhibitions such as Hong Kong InnoCarnival 2016, Hong Kong ICT Expo 2016, and PerCom Demo 2016.

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

There remain many challenging problems for distributed coordination in multi-robot system, as a special case of DiMEMS. Gathering, scattering, formation control and flocking are traditional but challenging problems in multi-robot systems. We aim to step into the area of distributed coordination in multi-robot system.

Another potential research direction will be educational multi-robot system. Robots have become a popular educational tool in some middle and high schools, as well as in numerous youth summer camps, raising interest in programming, artificial intelligence, and robotics among students. However, little research has been conducted for the educational multi-robot system, which provides richer functionalities compared to a single robot.

## 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)*

Microelectromechanical systems (MEMS) have reached a position of design maturity and are therefore ready for the mass-production of micro-scale devices. Past challenge focused on the engineering process of MEMS, and this project adds embedded intelligence to MEMS to obtain distributed intelligent MEMS (DiMEMS). We proposed a real-time programming model for DiMEMS and the corresponding runtime system to support distributed coordination with fault tolerance. To evaluate the proposed programming model and runtime system, we built a test-bed of distributed multi-robot system, which is one kind of DiMEMS. With high impact in both academic research and practical applications, this project is highly relevant and has special significance to the scientific and industrial community and society.

## Part C: Research Output

### 8. Peer-reviewed journal publication(s) arising directly from this research project

*(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.)*

| The Latest Status of Publications | | | | Author(s) | Title and Journal/ Book | Submitted to RGC | Attached to this report | Acknowledged the support of this Joint Research Scheme | Accessible from the institutional repository |
|---|---|---|---|---|---|---|---|---|---|
| Year of publication | Year of Acceptance *(For paper accepted but not yet published)* | Under Review | Under Preparation *(optional)* | ***(bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)* | *(with the volume, pages and other necessary publishing details specified)* | *(indicate the year ending of the relevant progress report)* | *(Yes or No)* | *(Yes or No)* | *(Yes or No)* |
| | 2016 | | | Yuvraj Sahni*, **Jiannong Cao**, Shan Jiang | "Middleware for Multi-Robot System", a chapter to appear in The Philosophy of Mission-Oriented Wireless Sensor Networks (Springer), Habib M. Ammari (Ed.). **[B2016]** | No | Yes | Yes | No |
| 2014 | | | | Tao Li*, **Jiannong Cao**, Junbin Liang, Junhao Zheng | "Towards Context-aware Medical Cyber-Physical Systems: Design Methodology and a Case Study", Cyber-Physical Systems, online, DOI: 10.1080/23335777. 2014.972686. 1(1): 5-23 (November 2014). **[J2014]** | Yes, 2014 | Yes | Yes | Yes |
| 2015 | | | | Lijie Xu*, Guihai Chen, **Jiannong Cao**, Shan Lin, Haipeng Dai, Xiaobing Wu, Fan Wu | "Optimizing Energy Efficiency for Minimum Latency Broadcast in Low-Duty-Cycle Sensor Networks", ACM Transactions on Sensor Networks (TOSN). 11(4) (March 2015). **[J2015]** | No | Yes | Yes | Yes |

| The Latest Status of Publications | | | | Author(s) *(**bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)* | 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)* | | | | | | |
| 2016 | | | | Weiping Zhu*, **Jiannong Cao, Michel Raynal** | "Predicate Detection in Asynchronous Distributed Systems: A Probabilistic Approach", IEEE Transactions on Computers (TC). 65(1): 173-186 (January 2016). **[J2016a]** | No | Yes | Yes | Yes |
| 2016 | | | | Junbin Liang*, Tao Li, **Jiannong Cao** | "Distributed Intelligent MEMS: A Survey and a Real-time Programming Framework", ACM Computing Surveys. 9(4): 39:1-39:28 (March 2016). **[J2016b]** | Yes, 2014 | Yes | Yes | Yes |
| 2017 | | | | Md Zakirul Alam Bhuiyan*, Jie Wu, Guojun Wang, **Jiannong Cao**, Wenjun Jiang, Mohammed Atiquzzaman | "Towards Cyber-Physical Systems Design for Structural Health Monitoring: Hurdles and Opportunities", ACM Transactions on Cyber-Physical Systems. (April 2017). **[J2017]** | No | Yes | Yes | Yes |

**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. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

| 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)* |
|---|---|---|---|---|---|---|
| October/2014 /Nara, Japan | Device Collaboration for Stability Assurance in Distributed Cyber-Physical Systems | The 33rd International Symposium on Reliable Distributed Systems (SRDS 2014) **[C2014]** | No | Yes | Yes | Yes |
| August/2016/ Waikoloa, Hawaii, USA | Programming Large-Scale Multi-Robot System with Timing Constraints | 25th International Conference on Computer Communication and Networks (ICCCN 2016) **[C2016]** | No | Yes | Yes | Yes |
| May/2017/Atlanta, GA, USA | Tag Size Profiling in Multiple Reader RFID Systems | IEEE International Conference on Computer Communications (INFOCOM 2017) **[C2017a]** | No | Yes | Yes | No |
| July-August/2017/Vancouver, Canada | Uniform Circle Formation by Asynchronous Robots: A Fully-Distributed Approach | 26th International Conference on Computer Communications and Networks (ICCCN 2017) **[C2017b]** | No | Yes | Yes | No |

**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 |
|---|---|---|---|
| Nil | | | |

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

1. We are collaborating with the Shenzhen Huawei Technologies Corporation to develop a smart IoT (Internet of Things) platform, which can be used to implement intelligent applications in the future such as smart home, smart vehicle, smart medicine, etc. Our language can be used to program real-time applications in these fields, which are highly needed by users.

2. We are collaborating with the Carnegie Mellon University to provide robust and reliable programming interfaces that can manage the reconfiguration of ensembles with millions of MEMS microrobots into dynamic, 3-Dimensional forms.

**12. Public access of completion report**
*(Please specify the information, if any, that cannot be provided for public access and give the reasons.)*

| Information that cannot be provided for public access | Reasons |
|---|---|
| Nil | |