RGC Ref. No.:
UGC/FDS11/E03/19
(please insert ref. above)

RESEARCH GRANTS COUNCIL
COMPETITIVE RESEARCH FUNDING SCHEMES FOR THE LOCAL SELF-FINANCING DEGREE SECTOR

FACULTY DEVELOPMENT SCHEME (FDS)

Completion Report

(for completed projects only)

Submission Deadlines:
1. *Auditor's report with unspent balance, if any: within **six** months of the approved project completion date.*
2. *Completion report: within **12** months of the approved project completion date.*

Part A: The Project and Investigator(s)

1. Project Title

Energy-efficient joint resource scheduling for wireless networked control systems

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

Research Team	Name / Post	Unit / Department / Institution
Principal Investigator	ZHAO Yingchao / Associate Professor	School of Computing and Information Sciences / Caritas Institute of Higher Education
Co-Investigator(s)	Dr. LI Minming / Professor	Department of Computer Science / City University of Hong Kong

3. Project Duration

	Original	Revised	Date of RGC / Institution Approval *(must be quoted)*
Project Start Date	01/01/2020	N/A	N/A
Project Completion Date	30/06/2022	N/A	N/A
Duration *(in month)*	30	N/A	N/A
Deadline for Submission of Completion Report	30/06/2023	N/A	N/A

<u>Part B: The Final Report</u>

5. Project Objectives

5.1 Objectives as per original application

1. For the JRS problem with no speed change for the CPU, we will study different special patterns which exist in the real systems for the three-phase jobs and try to design polynomial time algorithms or prove NP-hardness together with designing approximation algorithms with guaranteed performance.
2. For the JRS problem where the CPU can change its speed when executing jobs, we will study two sub problems, minimizing makespan given energy budget and minimizing energy given required makespan. We aim to design good algorithms for different types of jobs classified according to the relationship between the feasible intervals among jobs.
3. For the pure DVS scheduling where CPU can change its speed when executing normal jobs, we plan to study the property of energy optimal schedules for new jobs given a prefixed speed curve for existing system jobs. Polynomial time algorithms or NP-hardness with approximation is expected to be achieved.
4. For the JRS problem with online jobs, we aim to propose good algorithms for both the setting where only three-phase jobs exist and the setting where there are also a set of pre-scheduled system jobs giving a base speed curve for the three-phase jobs. Experiments will be carried out to validate the performance of the proposed algorithms on top of the theoretical analysis.

5.2 Revised objectives

Date of approval from the RGC: ____________________

Reasons for the change: ____________________

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1.

2.

3. ....

5.3 Realisation of the objectives

(Maximum 1 page; please state how and to what extent the project objectives have been achieved; give reasons for under-achievements and outline attempts to overcome problems, if any)

For the first objective, we have studied two special patterns which exist in the real systems. For the h-1-1 pattern where the computing and actuating segments are restricted to have unit-size executing time, we present an optimal algorithm that utilizes the intervals of network resource utilization of 100% to prune the search space to find the solution. For the 1-m-1 pattern where both sensing and actuating segments have unit-size executing time, we propose an optimal algorithm that exploits a novel backtracking strategy to adjust the timing parameters of the tasks so that there exist no intervals of network resource utilization larger than 100% obtained in the two-stage decomposition method. For the general case, we propose a heuristic solution to find the feasible schedule based on the greedy strategy of modifying the segments in the interval of either network resource utilization or computing resource utilization larger than 100%.

For the second objective, we mainly considered the case where a limited amount of energy is available to the system and the objective is to minimize the makespan given energy budget because most applications in wireless networked control systems use batteries as the power supply. We proved that this scheduling problem is strongly NP-hard even if the actuating segments are the same. We designed a dynamic programming based polynomial-time algorithm for a fixed number of types of tasks. For the case where makespan is given and the objective is to minimize the energy consumption, we designed an algorithm.

For the third objective, we have designed a polynomial-time Dynamic Voltage Scheduling (DVS) algorithm that can schedule all the jobs with minimum power consumption with given prefixed speed curve. In this algorithm, we need to divide the whole timeline into smaller intervals based on each job's release time and due time, and then divide each hard-core job into smaller jobs. By calculating the intensity of each interval, we can remove the full-occupied interval together with the smaller jobs assigned inside and repeat the above steps until all the jobs are processed.

For the fourth objective, we proved that it is NP-hard to get the optimal online schedule. Since we discovered that the actuating segments have far less load than sensing segments and computing segments in real applications, we explored the scenario where all the tasks are of the pattern a-b-1 and the priority order of the sensing segments on the network resources is fixed. We proposed an approximation algorithm of complexity $O(n^2)$. In the experiments, we found that the schedule returned by this approximation algorithm is near-optimal if the number of tasks in each type is much greater than 1, and we also observed that the shortest remaining processing time order performs the best in al situations.

5.4 Summary of objectives addressed to date

Objectives *(as per 5.1/5.2 above)*	**Addressed** *(please tick)*	**Percentage Achieved** *(please estimate)*
For the JRS problem with no speed change for the CPU, we will study different special patterns which exist in the real systems for the three-phase jobs and try to design polynomial time algorithms or prove NP-hardness together with designing approximation algorithms with guaranteed performance.	√	100%
For the JRS problem where the CPU can change its speed when executing jobs, we will study two sub problems, minimizing makespan given energy budget and minimizing energy given required makespan. We aim to design good algorithms for different types of jobs	√	100%

classified according to the relationship between the feasible intervals among jobs.		
For the pure DVS scheduling where CPU can change its speed when executing normal jobs, we plan to study the property of energy optimal schedules for new jobs given a prefixed speed curve for existing system jobs. Polynomial time algorithms or NP-hardness with approximation is expected to be achieved.	√	100%
For the JRS problem with online jobs, we aim to propose good algorithms for both the setting where only three-phase jobs exist and the setting where there are also a set of pre-scheduled system jobs giving a base speed curve for the three-phase jobs. Experiments will be carried out to validate the performance of the proposed algorithms on top of the theoretical analysis.	√	100%

6. Research Outcome

6.1 Major findings and research outcome
(Maximum 1 page; please make reference to Part C where necessary)

In the study of Objective 1, we find that scheduling three-segment tasks is NP-hard. The straight execution order of each three-segment task makes the problem difficult. We considered two special patterns: h-1-1 and 1-m-1 and studied the properties of optimal schedule, which can help us detect whether some task set is schedulable. In h-1-1 case, by repeatedly updating the timing parameters of each task, we check the existence of the effective network overload interval, and then use earliest deadline first strategy to schedule the network and computing segments in parallel based on their effective deadlines. In 1-m-1 case, we use backtracking search to eliminate all virtual network overlade intervals and check whether the task set is schedulable. The algorithms and experiment results are presented in the paper [C1].

In the study of Objective 2, we first proved the NP-hardness. Then we used dynamic programming to schedule tasks when the speed of CPU/GPU can be changed. We classified the tasks according to the relationship between the feasible intervals among tasks. The running time of the algorithms is related to the types of tasks. Since the types of sensors in WNCS is usually a constant, the number of task type is also a constant, which makes the running time of dynamic programming a polynomial function. Given the total power consumption, we designed an algorithm to minimize the makespan. These works are presented in the papers [C2] and [J1].

In the study of Objective 3, we designed a polynomial-time algorithm that can optimally schedule the tasks given a prefixed speed curve for existing system jobs. The system tasks commonly exist in the real applications. The algorithm fills the gap between the optimal schedule and the result obtained by DVS ignoring the system jobs. These works are presented in the paper [J1].

In the study of Objective 4, we considered online CRS problems. Because the third segment only sends the decision to actuators which is usually of small size compare with the first two segments. Therefore, the a-b-1 patterns are discussed. We designed an algorithm to schedule the a-b-1 tasks. The running time is $O(Kn^{5K+2})$ where K is the types of tasks. If the priority order of the sensing segments is given, the earliest staring time on the computing resource can be determined, and we can design an algorithm with running time $O(n^2)$ which is much faster than the one without priority order. Additionally, we observed that the schedule returned by this algorithm was near optimal when the number of tasks in each type is much greater than 1. These works are presented in the papers [C2] and [J1].

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

In many applications of wireless networked control systems, the execution order of tasks is usually ignored which causes waste of system resources or tasks unfinished in time. Our project proposed scheduling algorithms that can be used in those applications to increase the efficiency and utilize both the computing resource and the network resources. These algorithms are especially useful for the scenario where only a few types of sensors are used.

For the future development of this project, we can apply our scheduling algorithms in the real WNCS applications, for example, robocars. The parameters of the three-segment tasks will be collected and used as the input of the scheduling algorithms. The scheduling algorithms can either precompute an optimal schedule for all the tasks or run the online ECRS algorithms according to the priority order of the tasks. It is expected that the scheduling algorithms can increase the utilization rate of the application as well as reduce the energy consumptions. We expect that the research outcomes of this project can contribute to more WNCS applications, for example, self-driving vehicles in the future.

7. Layman's Summary

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

Wireless networked control system (WNCS) is a control systems where different system components (including sensors, actuators and controllers) exchange the control signals and feedback signals among them in the form of information packages via the wireless network. Taking the self-driving vehicle as an example, the typical tasks work as follows: the sensors first perceive the environment and send the data to the controller via wireless network; then the controller handles the data and calculates the best decision using computing resource (CPU/GPU); finally, the decision is sent to the actuators via wireless network. Therefore, two resources (computing resources and network resources) are used. To make sure that the tasks are executed before their due time, we consider both resources and design efficient algorithms to schedule the tasks.

Furthermore, if the total workload is too much, we can adjust the speed of the processor to make the tasks satisfy the time constraints using Dynamic Voltage Scheduling (DVS). However, higher processor speed causes more energy consumption. We design various algorithms to balance the processor speed and power consumption while guaranteeing the time constraints. The overall research outcomes of this project can contribute to many WNCS applications, like self-driving vehicles.

Part C: Research Output

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 RGC's funding support by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) *(denote the correspond-ing 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 RGC *(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)*						
			Yes	[J1] Vincent Chau, Chenchen Fu, Shu Han, Song Han, Minming Li, Peng Wu, Yizheng Zhang, and Yingchao Zhao*	Composite Resource Scheduling for three-segment jobs in Networked Control Systems.	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 conference abstract)

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 RGC *(Yes or No)*	Accessible from the Institutional Repository *(Yes or No)*
December 2021, Dortmund, Germany	[C1] Composite Resource Scheduling for Networked Control Systems	42nd IEEE Real-Time Systems Symposium	No	Yes	Yes	Yes
	[C2] Energy-Efficient Composite Resource Scheduling in Networked Control Systems.	Submitted to RTSS2023 Under reviw	No	Yes	No (Acknowledge ment will be added when it is accepted)	No (It will be accessible when it is accepted)

10. Whether Research Experience And New Knowledge Has Been Transferred / Has Contributed To Teaching And Learning

(Please elaborate)

The proposed project makes great effort to create novel teaching topics and make the students well prepared for the design challenges of networked control systems. The developed research outcomes, including greedy algorithms, approximation algorithm, computational complexity analysis, NP-hardness proof, have been seamlessly integrated into the course offered by the PI. The corresponding course materials and project information become available to the students to encourage them to design high-efficiency programs.

11. 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

12. Other Impact

(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, teaching enhancement, etc.)

This research is conducted in close relation with our research partners from different universities, for example, University of Connecticut, City University of Hong Kong, Southeast University. The outcomes of this research have direct impacts on task scheduling in networked control systems by making the research outcomes publicly accessible to the industry.

13. Statistics on Research Outputs

	Peer-reviewed Journal Publications	Conference Papers	Scholarly Books, Monographs and Chapters	Patents Awarded	Other Research Outputs (please specify)	
No. of outputs arising directly from this research project		1 published 1 under-review			Type	No.

14. 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**
N/A	

[C1]. Peng Wu*, Chenchen Fu*, Tianyu Wang, Minming Li, Yingchao Zhao, Chun Jason Xue, Song Han: Composite Resource Scheduling for Networked Control Systems. RTSS 2021: 162-175

[C2]. Vincent Chau*, Chenchen Fu, Shu Han, Song Han, Minming Li, Peng Wu, Yizheng Zhang, and Yingchao Zhao: Energy-Efficient Composite Resource Scheduling in Networked Control Systems. Submitted to RTSS 2023, under review.

[J1]. Vincent Chau, Chenchen Fu, Shu Han, Song Han, Minming Li, Peng Wu, Yizheng Zhang, and Yingchao Zhao*: Composite Resource Scheduling for three-segment jobs in Networked Control Systems. Draft.