RGC Ref.: N_HKUST620/15 NSFC Ref. : 61531166003
(please insert ref. above)

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

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

Part A: The Project and Investigator(s)

1. Project Title

Highly parallel algorithms for fluid-structure interaction problems and applications

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. Wang Xiao-Ping	Prof. Cai Xiao-Chuan
Post	Chair Professor	Professor
Unit / Department / Institution	Department of Mathematics/The Hong Kong University of Science & Technology Department of Mathematics/The Chinese University of Hong Kong	Shenzhen Institutes of Advanced Technology/ Chinese Academy of Sciences Computer Network Information Center/ Chin
Contact Information	mawang@ust.hk	Xiaochuan.cai@siat.ac.cn
Co-investigator(s) *(with title and institution)*	Prof. Chung Eric Tsz-Shun, Dr. Luo Li, Dr. Du Jie	Prof. Zhao Yubo, Prof. Lu Zhonghua, Dr. Chen Rongliang, Dr. Zhang Jian, Dr. Liang Shan

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	Jan 1, 2016		
Project Completion date	Dec 31, 2019		

Duration *(in month)*	48		
Deadline for Submission of Completion Report	Dec 31, 2020		

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

5. Project Objectives

5.1 Objectives as per original application

1. *More accurate mathematical models for hemodynamics*
2. *Monolithic coupling for FSI problems*
3. *High resolution schemes on unstructured moving meshes*
4. *Highly scalable parallel solution algorithms*
5. *Numerical experiments with patient-specific geometry/material data*

5.2 Revised Objectives

Date of approval from the RGC: ____________________

Reasons for the change: ____

____

6. Research Outcome

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

1) We incorporated the impedance and the resistance boundary conditions to the cardiovascular system for the main aorta and coronary arteries, respectively. We developed a fully coupled approach for the fluid-structure interaction problems. In the fully coupled approach, incompressible Navier-Stokes equations for the fluid flows is described in an arbitrary Lagrangian-Eulerian (ALE) framework [J2, J3] in which a harmonic elliptic equation is employed to describe the motion of the fluid domain. The elasticity equation for the structure deformation is formulated in a Lagrangian framework and three coupling conditions are implicitly enforced in the variational forms of the fluid and structure equations.

2) We investigated the use of a new discontinuous Galerkin method [J1, J6] for a nonlinear flow system motivated by realistic blood flow modeling. We demonstrated that the use of this new methodology allows the construction of more accurate approximate solutions with enhanced mass conservation property. We expect that this method will be able to model more realistic situations with clinical data.

3) We investigated how to create deformable mesh of high quality based on linear elastic equations, via the construction of local Young's modulus and Poisson ratio. On the one hand, we applied the local adjustment approach to change the distribution of the mesh points. On the other hand, we tried to use the extended finite element method with level-set enriched basis functions to capture the motion of the fluid-solid interface, so that the discontinuity of variables can be correctly revealed at the interface. In both of these two methods, we introduced the idea of "mesh velocity" to the ALE description of the fluid [J2, J3].

4) An efficient finite element method on unstructured meshes is introduced to cope with the complex geometry of the solid surfaces. We extend the GNBC to surfaces with complex geometry by including its weak form along different normal and tangential directions in the finite element formulation. To efficiently solve the systems, we present a highly parallel solution strategy based on domain decomposition techniques. We validate the newly developed solution method through extensive numerical experiments, particularly for those phenomena that cannot be achieved by two-dimensional simulations [J4, J5].

5) The blood flow is often smooth in a healthy artery, but may become locally chaotic in a diseased artery with stenosis, and as a result, a traditional solver may take many iterations to converge or does not converge at all. To overcome the problem, we developed a nonlinearly preconditioned Newton method in

which the variables associated with the stenosis are iteratively eliminated and then a global Newton method is applied to the smooth part of the system [C1]. Numerical experiments for several cerebral arteries demonstrate the superiority of the proposed algorithm over the classical method with respect to some physical and numerical parameters.

6) We studied the generation of multiple meshes for computation. We first created a suitable mesh which is able to depict the geometry of interest, then upload the initial mesh to the supercomputer. After partitioning, we refined or coarsened the mesh in parallel to meet the requirement of multilevel calculations [J4, J5, C2]. For visualization purpose, the resulting solutions were interpolated onto a mesh with a suitable size. The operations of interpolating, restricting, and mapping between multiple meshes were realized which serve as the base for multilevel linear or nonlinear preconditioning.

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

It should be pointed out that for the numerical simulation of abdominal aortic blood flow, currently there are few large-scale calculation results involving the coronary arteries. Our results benefit from a set of efficient parallel solution algorithms independently developed by the team. We will develop more accurate biomechanical models and corresponding parallel solution algorithms to calculate the corresponding indicators for precisely predicting the AAA rupture risk.

For the coupled fluid-structure modeling, numerical study has been carried out based on fully implicit and fully coupled methods for solving linear elastic equations and incompressible Navier-Stokes equations. The team members used the parallel NKS algorithm to solve the hemodynamic problems in an aorta under pulsed pressure. Considering the anisotropy of blood arteries and the complicated blood flow in the abdominal aortic aneurysm, the current coupled fluid-structure model needs to be further improved, moreover, the interfacial conditions and other boundary conditions need to be further explored. We will consider some personalized parameters that are clinically measurable, such as the artery wall thickness, Young's modulus, and Poisson's ratio to achieve more realistic results.

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)

Application of fluid-structure interaction (FSI) methods in simulation-based medical planning is additionally demanding. Artery disease is closely associated with flow properties of the blood and with the interaction between the blood and the vessel wall. In particular, areas of turbulence, flow recirculation, or places where the artery wall is subject to low or oscillating shear stress are at higher risk for plaque formation and disease. Accurate modeling of these flow characteristics might enable better prediction of when and where artery disease will occur and lead to more accurate, less invasive, and more timely treatment.

Due to limitations in computing power, early hemodynamic simulations suffer from many constrains, such as the assumption of rigid vessels, the assumption of Newtonian fluid, and simple geometry etc. To accurately analyze hemodynamics, in this project, we develop an efficient and robust algorithm for solving the FSI problems based on trustworthy mathematical modeling, as well as to provide a set of highly-scalable medical planning software.

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) (***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)*						
2020 J1		Yes		**Li Luo*, Xiao-Chuan Cai**, David E. Keyes	Nonlinear preconditioning strategies for two-phase flows in porous media discretized by a fully implicit discontinuous Galerkin method, submitted to SIAM Journal on Scientific Computing, minor revision.	2020	Yes	Yes	No

2020 J2	2020			Xiang Li, Qiang Du, **Li Luo**, **Xiao-Ping Wang***	An energy-stable scheme for a 2D simple fluid-particle interaction problem, Journal of Computational Physics (2020) 109850.	2020	Yes	Yes	Yes
2018 J3	2018			Xing Zhang, **Li Luo, Xiao-Ping Wang***	A numerical study of fluid-particle interaction with slip boundary condition, *Numerical Mathematics: Theory, Methods and Applications*, 11 (2018), pp. 795-809.	31 Dec, 2017	No	Yes	Yes

2017 J4	2017			**Li Luo, Xiao-Ping Wang***, and **Xiao-Chuan Cai**	An efficient finite element method for simulation of droplet spreading on a topologically rough surface, *Journal of Computational Physics* 349 (2017), pp. 233-252.	31 Dec, 2017	No	Yes	Yes
2017 J5	2017			**Li Luo,** Qian Zhang, **Xiao-Ping Wang*, and Xiao-Chuan Cai**	A parallel finite element method for 3D two-phase moving contact line problems in complex domains, *Journal of Scientific Computing* 72 (2017), pp. 1119-1145.	31 Dec, 2017	No	Yes	Yes

2018 J6	2017			**Jie Du***, **Eric Chung**, Ming Fai Lam and **Xiao-Ping Wang**	Discontinuous Galerkin method with staggered hybridization for a class of nonlinear Stokes equations Journal of Scientific Computing, 76 (2018), pp. 1547–1577.	31 Dec, 2017	No	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)*
July/2018/St. John's, Newfoundland, Canada C1	A nonlinear elimination preconditioned inexact Newton algorithm for steady state incompressible flow problems on 3D unstructured meshes, **Li Luo***, **Rongliang Chen**, **Xiao-Chuan Cai**, and David E. Keyes,	The 25th International Conference on Domain Decomposition methods	2020	Yes	Yes	No

July/2015/Jeju Island, Korea C2	A parallel two-phase flow solver on unstructured mesh in 3D, **Li Luo*,** Qian Zhang, **Xiao-Ping Wang, and Xiao-Chuan Cai**	The 23th International Conference on Domain Decomposition methods	31 Dec 2017	No	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
Li Luo S1	PhD in Mathematics, The Hong Kong University of Science & Technology	August 20, 2013	Graduation: Mar 15, 2017

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

We collaborated with Prince of Wales Hospital Hong Kong, Beijing Tiantan Hospital, and Shenzhen Sun Yat-sen Cardiovascular Hospital to conduct high-precision and rapid simulation of blood flow in the human intracranial arteries, cardiovascular arteries, and abdominal arteries. The errors between calculated results and clinical measurement results are within 15%. We completed more than 200 cases of realistic arteries.

The two teams also organized several international workshops, which aim to bring together experts in this field from all over the world to discuss the latest development of high performance algorithms for PDEs and related applications.

a) International Workshop for High Performance Numerical Algorithms and Applications, January 8 - 12, 2018, Sanya, China.
b) "**Mini-symposium:** Parallel Algorithms for PDEs and Applications" at "20th IMACS World Congress", December 10-14, 2016, Xiamen University, China.
c) "**Mini-symposium:** Mathematical and Numerical Modeling in Biomechanics" at "2019 International Congress on Industrial and Applied Mathematics", July 15-19, 2019, Valencia, Spain.
d) "**Mini-symposium:** Research Progress on Parallel and Fast Algorithms for Partial Differential Equations" at "The 12th National Annual Conference on Computational Mathematics", July 31-Aug 4, 2019, Harbin, China.
e) "**Mini-symposium:** High Performance Algorithms and Applications in Computational Biomechanics" at "14th World Congress of Computational Mechanics", July 19-24, 2020, Paris, France.

12. Statistics on Research Outputs *(Please ensure the summary statistics below are consistent with the information presented in other parts of this report.)*

	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 [or conference]	6	2	0	0	