Shun Hing Institute of Advanced Engineering

信興高等工程研究所

Report and Research Highlights

2019 - 2020

July 2020

香　港　中　文　大　學
The Chinese University of Hong Kong

Printed in August 2020, this report contains information known as July 2020.

For further information, please visit our website: http://www.shiae.cuhk.edu.hk

Contents

Introduction of SHIAE

Mission of SHIAE

The MISSION of the Institute is to spearhead, conduct, promote and co-ordinate research in advanced engineering. There is no end to the list of areas to be explored and the plan is to give priority to research topics that are both exciting and innovative. The Institute also aspires to transferring its research results to industry for practical application and to put across to the community at large the role of engineering as a driving force for human development through educational activities.

As a pioneering institute exploring the forefront of the engineering science, The Shun Hing Institute of Advanced Engineering will

- spearhead state-of-the-art advanced engineering research
- create and sustain synergy with world-class researchers
- develop with and transfer to industries cutting edge technologies
- promote appreciation of engineering in society through educational programmes

The Shun Hing Education and Charity Fund was founded the late by Dr. William Mong Man Wai with the aim of enhancing educational opportunities for the younger generations. The Fund has already sponsored numerous educational and research programmes in Hong Kong, the Mainland, and overseas educational institutions. Himself an engineer and a firm believer in advancing the quality of life through the development of science and technology, Dr. Mong had been there to support the establishment and growth of this Institute from the beginning.

Centre of Excellence at CUHK

The Chinese University of Hong Kong (CUHK) is an internationally renowned institution of higher learning devoted to quality teaching and both academic and applied research. The University has established 29 research institutes and a number of research centres with a view to pursuing up-front research endeavours with focused goals and objectives. The Shun Hing Institute of Advanced Engineering plays a crucial part in the research infrastructure of CUHK which is committed to exciting research programmes in advanced engineering areas. The Institute is now in its second decade of development, and we are particularly pleased to have received continual staunch support and guidance from Mr. David Mong Tak Yeung, Chairman and CEO of the Shun Hing Group and the Shun Hing Education and Charity Fund.

As a strategic centre of excellence at CUHK, the Institute supports greater regional and international research collaborations, and strives to attract talent from the world over to achieve greater internationalization, a vision strongly advocated by every member of the University.

Commitment of the Faculty of Engineering

The Faculty of Engineering was founded in 1991 and was built upon existing strengths with added talent from all over the world. The Faculty has been able to attract some of the best minds. Many received their training in leading universities in North America, Great Britain and Australia. Most of them have extensive experience in industry and many are leaders in their fields. This team of top-notch talent is gathered to nurture local talent through educational programmes, and break new frontiers in research through innovative and exciting research endeavours.

The positioning of The Shun Hing Institute of Advanced Engineering in the William M.W. Mong Engineering Building is deliberate as a key nucleating point to integrate research endeavours in the Engineering Faculty and its neighbours. Our members join hands with their counterparts from the Faculties of Science and Medicine in many interesting research collaborations. It is the ambitious goal of the Faculty of Engineering that the Institute should become a lighthouse for the local technology landscape to herald the migration towards high value-added technology and an information economy.

The mission of the Institute is to spearhead, conduct, promote and co-ordinate research in advanced engineering. There is no end to the list of areas to be explored and the plan is to give priority to research topics that are both exciting and innovative. The Institute also aspires to transferring its research results to industry for practical application and to put across to the community at large the role of engineering as a driving force for human development through educational activities.

Building on Strength and The Way Ahead

Many of the Institute's research projects are built upon areas in which the Faculty has already achieved outstanding performance. These are areas that have great potential for further technological advancement and in line with industrial development in Hong Kong. The Institute provides a vibrant R&D environment to spur new discoveries and speed up their translation into applications. Since 2012, we have expanded our scope to cover new frontiers in Renewable Energy striving to answer tomorrow's energy challenges. In year 2017, we further expand the research scope in Multimedia Technologies to include Artificial Intelligence, Big Data Analytics and Deep Learning as well. In the past few years, the Engineering Faculty has recruited many young and talented researchers, and the Institute has given priority to provide them with the needed research support as far as possible.

Technology Transfer

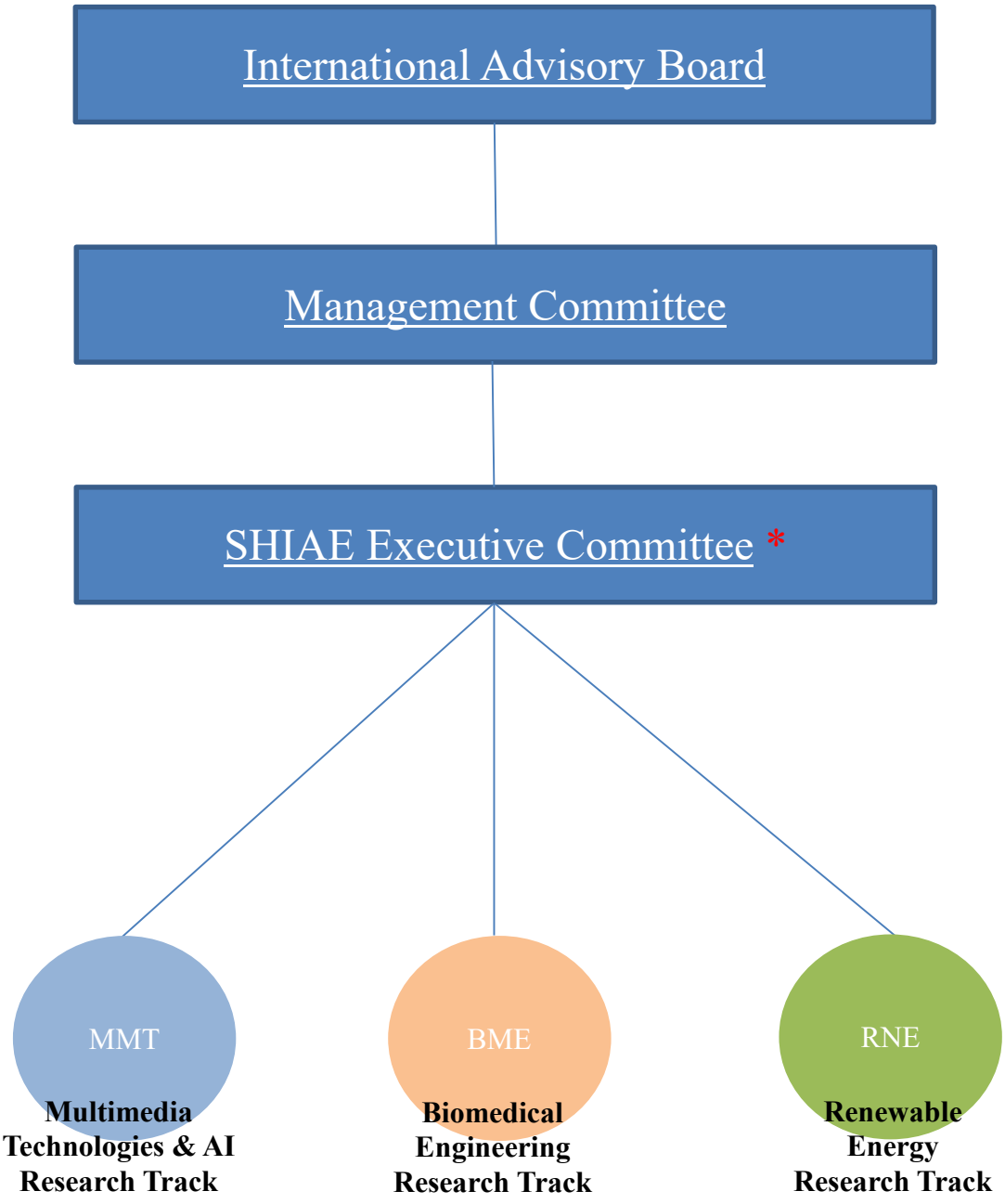
Synergy with industry is the ultimate goal of research and development in Hong Kong. External experts have been brought in to the Institute to lead research projects that could benefit the industrial sector.

The technology transfer arm of the Faculty of Engineering plays an important role in the traffic between the Institute and industry. The Institute houses an array of top-notch research and development activities encompassing contract research, spin-off companies, and consultancies.

Contribution to Society

The Institute has been making contributions to the progress of Hong Kong through a wide range of educational activities like training courses, seminars, symposiums which disseminate the latest technologies to promote appreciation of engineering in society and arouse interest of the younger generations in engineering.

Organization



We also provide support and sponsorship to the Faculty of Engineering in organizing prestigious academic conferences in Hong Kong so as to raise our international profile.

* In compliance with CUHK's guidelines in strengthening the governance of research units, an Executive Committee was formed to oversee the daily operation of the Institute in April 2020, headed by the Director, while the Dean of Engineering served as the Chairman of the Management Committee.

Composition of International Advisory Board

Chairman:

Dr. David T.Y. MONG 蒙德揚先生

Chairman & Group CEO
Shun Hing Electronic Holdings Limited
Hong Kong

Members:

Professor Victor ZUE

Delta Electronics Professor of Electrical Engineering and Computer Science
Massachusetts Institute of Technology
U.S.A

Dr. Harry SHUM 沈向洋博士

Executive Vice President, Technology and Research
Microsoft Corporation
U.S.A.

Professor Yongmin KIM

Affiliate Professor
University of Washington
U.S.A.

Professor C.C. Jay KUO

Professor of Electrical Engineering and Computer Science
University of Southern California
U.S.A.

Professor Paul, Kit-lai YU

Provost, Revelle College, Jacobs School of Engineering
University of California, San Diego
U.S.A.

Professor Wai-yee CHAN 陳偉儀教授

Pro-Vice-Chancellor/ Vice-President
Li Ka Shing Professor of Biomedical Sciences
The Chinese University of Hong Kong
Hong Kong

Professor Wing-shing WONG 黃永成教授

Choh-Ming Li Professor of Information Engineering
The Chinese University of Hong Kong
Hong Kong

Professor Martin Ding Fat WONG 黃定發教授

Dean of Engineering
The Chinese University of Hong Kong
Hong Kong

Professor Pak Chung CHING 程伯中教授

Director of Shun Hing Institute of Advanced Engineering
Choh-Ming Li Professor of Electronic Engineering
The Chinese University of Hong Kong
Hong Kong

Composition of Management Committee

Chairman:	**Professor Martin D.F. WONG** *Dean of Engineering* *(from 15 May 2020)*
	Professor Pak Chung CHING *Director, Shun Hing Institute of Advanced Engineering (ex-officio)* *(till 14 May 2020)*
Deputy Chairman:	**Professor Pak Chung CHING** *Director, Shun Hing Institute of Advanced Engineering (ex-officio)* *(from 15 May 2020)*
Members:	**Professor Martin D.F. WONG** *Dean of Engineering (ex-officio)* *(till 14 May 2020)*
	Mr. Gary NG *Managing Director of Shun Hing Technology Co., Limited* *(from 9 March 2020)*
	Mr. Terrence CHAN *Managing Director of Shun Hing Electronic Holdings Limited* *(till 8 March 2020)*
	Professor Jack C.Y. CHENG *Department of Orthopaedics and Traumatology*
	Professor Soung-chang LIEW *Department of Information Engineering* *(from 1 March 2020)*
	Professor Jianwei HUANG *Department of Information Engineering* *(till 29 February 2020)*
	Professor Tan LEE *Department of Electronic Engineering*
	Professor Wei-Hsin LIAO *Department of Mechanical and Automation Engineering*
	Professor Anthony Man-cho SO *Department of Systems Engineering and Engineering Management*
	Professor Raymond Kai-yu TONG *Department of Biomedical Engineering*
Member and Secretary:	**Professor John C.S. LUI** *Department of Computer Science and Engineering*

Composition of Executive Committee

(*with effect from April 1, 2020*)

Chairman: **Director, Shun Hing Institute of Advanced Engineering**
(ex officio)
- **Professor Pak Chung CHING**

Members: **Professor Jonathan Chung Hang CHOI**
Department of Biomedical Engineering

Professor John C.S. LUI
Department of Computer Science and Engineering

Professor Li ZHANG
Department of Mechanical and Automation Engineering

Secretary: **Ms Natalie TSANG**
Shun Hing Institute of Advanced Engineering

Shun Hing Visiting Scholars/ Fellows

The Institute has launched a Shun Hing Distinguished Scholar Program with an aim to attract distinguished scholars to pursue research collaboration with our faculty and to strengthen our research profile. The following scholars visited to work either on a short term or on a longer term engagement with the Institute between 2019 and 2020.

Shun Hing Fellows and Research Associate:
(in alphabetical order)

Dr. DING Wenlong *Shandong University, China*	2019-2020
Dr. JIN Jiangliang *Singapore University of Technology and Design, Singapore*	2019-2020
Dr. LI Xiaoyi *Tsinghua University, China*	2018-2019
Dr. QI Qiuli *The Chinese University of Hong Kong, Hong Kong*	2019-2020
Dr. WANG Jiaqi *Hong Kong University of Science and Technology, Hong Kong*	2019-2020
Dr. XIN Zhen *Aalborg University, Denmark*	2018-2019
Dr. YEUNG Kan Kan *Hong Kong University of Science and Technology, Hong Kong*	2019-2020
Mr. MENG Hu *National Taiwan University, Taiwan*	2019-2020

Financial Status of SHIAE

INCOME AND EXPENDITURE STATEMENT 2019-2020

(Fiscal Year: April 1, 2019 – March 31, 2020)

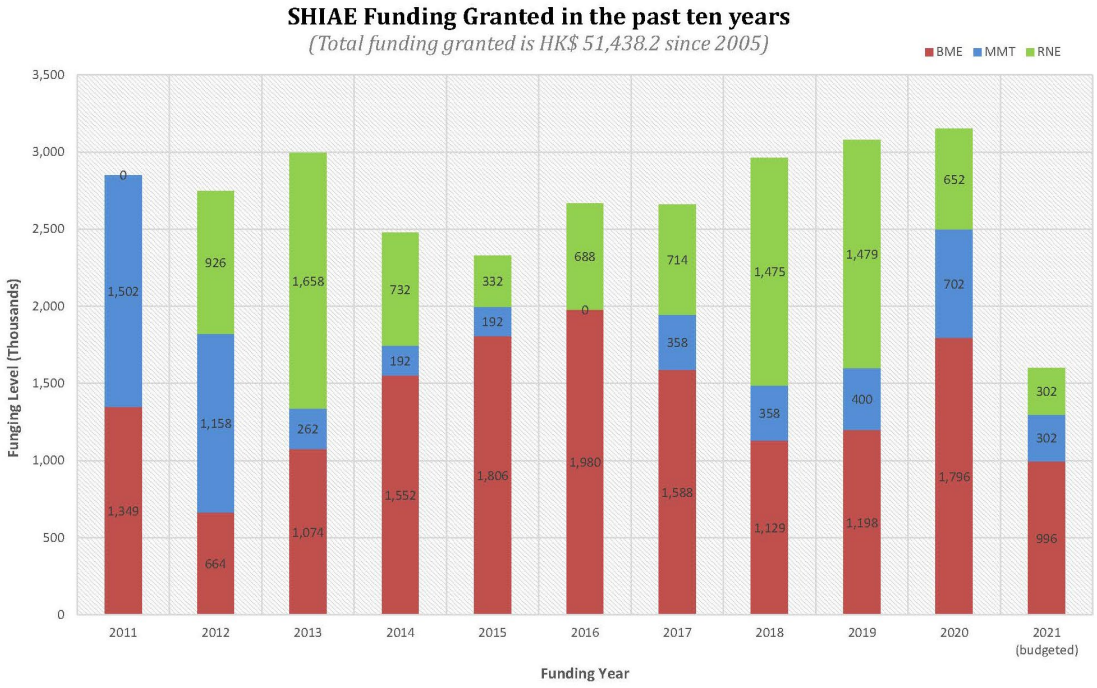
	Notes	As at 31 March 2020	As at March 31, 2019
INCOME			
Funding Source			54,500,000
Accumulated fund brought forward		16,509,627	-
Interest and investment income		196,961	7,365,177
Sub-total:		16,706,588	61,865,177
EXPENDITURE			
Research Funding	(1)	3,077,000	43,611,200
Remaining fund from completed projects		-75,560	-3,508,832
Operating cost		487,126	5,253,182
Sub-total:		3,488,566	45,355,550
BALANCE as at 31 March 2020		**13,218,021**	**16,509,627**

APPROVED BUDGET 2020-2021

(Fiscal Year: April 1, 2020 – March 31, 2021)

	Notes	
INCOME		
Accumulated fund brought forward		13,218,021
Projected interest and investment income		200,000
Sub-total:		13,418,021
EXPENDITURE		
Research Funding		
On-going projects (Year 2019 batch)	(2)	1,550,000
Newly funded projects (Year 2020 batch)	(2)	1,600,000
Operating cost		
Staff and Admin. cost		370,000
Facility Upgrade		20,000
Distinguished lectures		10,000
Activities Sponsorship		100,000
Sub-total:		3,650,000
Projected Balance in March 2021		**9,768,021**

Note (1) Annualized Research Funding to each research areas granted in the past ten years.



This figure shows the distribution of the SHIAE funding granted to each track of research projects, namely Biomedical Engineering (BME), Multimedia Technology & AI (MMT) and Renewable Energy (RNE) annually.

Note (2) Total funding for each batch of projects (in HK$ '000)

Funding Year / (No. of projects)	2021 (committed)	2020	2019	2018	2017	2005 - 2016
Year 2005 / (6)	-	-	-	-	-	6,108
Year 2006 / (5)	-	-	-	-	-	3,175
Year 2007 / (7)	-	-	-	-	-	4,146
Year 2008 / (4)	-	-	-	-	-	3,976
Year 2009 / (5)	-	-	-	-	-	3,306
Year 2010 / (5)	-	-	-	-	-	2,789.2
Year 2011 / (4)	-	-	-	-	-	2,476
Year 2012 / (5)	-	-	-	-	-	3,040
Year 2013 / (4)	-	-	-	-	-	2,948
Year 2014 / (3)	-	-	-	-	-	2,004
Year 2015 / (4)	-	-	-	-	-	2,656
Year 2016 / (4)	-	-	-	-	1,213	1,340
Year 2017 / (4)	-	-	-	1,447	1,447	-
Year 2018 / (4)	-	-	1,527	1,515	-	-
Year 2019 / (4)	-	1,550	1,550	-	-	-
Year 2020 / (5)	1,600	1,600	-	-	-	-
WOSP2007	-	-	-	-	-	25
	1,600	3,150	3,077	2,962	2,660	37,989.2

Accumulated Total: **HK$51,438.200**

This table shows the detail amount of SHIAE funding granted to each batch of research projects. The subtotal amount of **1.6 million** budgeted for 2021 is committed to support research projects in July 2021.

Research - *Outstanding Research Highlights*

Commercialization Plans of completed projects

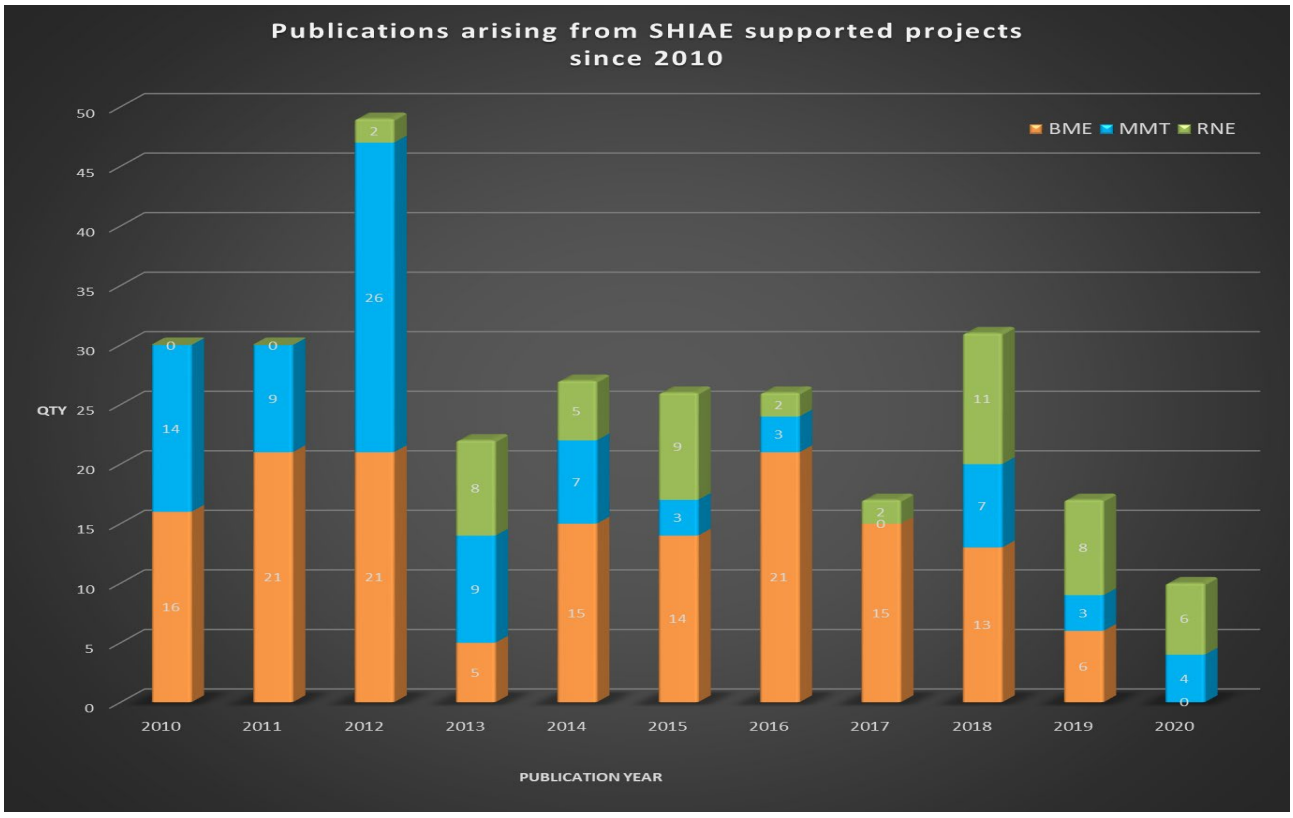
- Tunable spindle using self-excited vibration for high efficiency renewable electric generators
by **Professor Wei-Hsin Liao** *(page 42 - 43)*

- Development of a Novel Robotic Manipulator for Confined Space Surgery
by **Professor AU, Kwok Wai Samuel** *(page 76)*

- Development of an Inertial Microfluidics Based Approach for the Isolation of Mitochondria from Biological Samples
by **Professor Megan Yi-Ping HO** *(page 83)*

Academic Publications

So far **60 projects** have been successfully completed and **441 articles** arising from the results of these research projects have been published in international conference proceedings and journals. The other **8 on-going projects** are also progressing well with encouraging results produced. All publications generated by each individual projects are kept in the archive of SHIAE office. The chart below shows the number of academic publications produced from 2010 onward.



The full list of publications can also be downloaded from the webpage of SHIAE at www.shiae.cuhk.edu.hk/research.htm

Renewable Energy Track

Research Reports In Renewable Energy

Newly Funded Projects (2020-2022)	* Modeling of environmental effects on performance degradation of offshore wind turbine blades made by carbon fiber reinforced plastics (CFRPs)
Continuing Projects (2019-2021)	*Energy Management System for Large-scale Electric Vehicle Charging with Renewable Generation and Energy Storage
(2018-2020)	* Development of a Novel Cooling Tower with Free Daytime Radiative Cooling for Reducing Energy Consumption in Buildings
	* Megahertz Current Sensor for Megahertz Renewable Energy Converter
	* Development of High-Performance Triboelectric Nanogenerators for Renewable Blue Energy Harvesting
Completed Projects (2017-2019)	* Tunable spindle using self-excited vibration for high efficiency renewable electric generators

The following reports are enclosed in “Research Highlights” printed in June 2019.

Completed Projects (2016-2018)	* Robust NiMo–yttria Stabilized Zirconia (NiMo–YSZ) Anode Materials for Solid Oxide Fuel Cells

The following reports are enclosed in “Research Highlights” printed in July 2018.

Completed Projects (2015-2017)	* Experimental and modeling study of biodiesel combustion

The following reports are enclosed in “Research Highlights” printed in August 2017.

Completed Projects (2013-2015)	* Earth-Abundant Metal/Metal Oxide Nanostructures for Rechargeable Li-Air Batteries: Catalyst Design and Mechanistic Investigation * Graphene-based asymmetric supercapacitors with high energy density for clean energy storage systems

The following reports are enclosed in “Research Highlights” printed in July 2015.

Completed Projects (2012)	* Vibration Energy Harvesting Utilizing Multifunctional Phononic Meta-Materials and Structures
Completed Projects (2012)	* Understanding Electron and Phonon Transport in Boron Carbide Nanowires for Thermoelectric Energy Conversion * Ternary Hybrid Polymer/Nanocrystal Bulk Heterojunction Solar Cells with Cascade Energy-Level Alignmen

(Funded Year)

MODELING OF ENVIRONMENTAL EFFECTS ON PERFORMANCE DEGRADATION OF OFFSHORE WIND TURBINE BLADES MADE BY CARBON FIBER REINFORCED PLASTICS (CFRPS)

Principal Investigator: Professor ZHANG, Weizhao
Department of Mechanical & Automation Engineering
CUHK

Project Start Date: 1 September 2020

ABSTRACT

The pressing need to reduce greenhouse gas emissions has led to increasing installation of offshore wind turbines, which usually have blades made with carbon fiber reinforced plastics (CFRPs) that have high performance-to-weight ratios. Modern methods utilize finite element analysis (FEA) to design CFRP blades at high speed and low cost, but none of these FEA models consider degradation of CFRPs under extreme offshore conditions, which have been experimentally proved to significantly impair long term performance of blades. To efficiently design CFRP blades with long lifecycle and avoid high safety factors, this project aims to develop a cutting-edge MD (molecular dynamics)-FEA integrated modeling method to simulate performance degradation of CFRP wind turbine blades with offshore environmental effects included. Upon completion, a state-of-the-art numerical tool will be established to aid material selection and new material design for CFRPs that are to be applied under marine or other harsh conditions. The underlying principles about electrochemistry erosion at CFRP-metal interfaces can also be obtained to guide construction of CFRP part joints and selection of component materials for water-involved applications. Furthermore, a flexible numerical tool that can customize blade design and guide blade damage monitor can also be developed.

INNOVATION AND PRACTICAL SIGNIFICANCE:

The proposed research work will lead to the first-ever multiscale modeling method to analyze and predict performance degradation of CFRPs under extreme offshore working conditions, i.e., seawater immersion and high temperature. At microscopic and mesoscopic levels, the method will provide (1) innovative mechanical-chemical-physical analysis to investigate the degradation mechanisms that are difficult to be captured by pure experiments; and (2) cost-efficient numerical characterization of CFRPs constitutive law with environmental effects considered. The obtained constitutive law is then to be implemented into the state-of-the-art macroscopic model for offshore wind turbine blade design optimization and damage monitor. Upon completion, this method can achieve efficient design and accurate failure prediction for blades during their lifecycles. Hence, this method can greatly reduce manufacturing, usage and maintenance cost of offshore wind turbines, expanding application of renewable wind energy significantly. Furthermore, this modeling method can be expanded to other applications under extreme environment, such as marine vehicles and buildings that can enlarge space for human activities and alleviate rising issues resulted from limited resources.

PROJECT OBJECTIVES:

1. To numerically investigate performance degradation of carbon fiber reinforced plastics (CFRPs) under salty-wet-hot conditions that are common under extreme offshore environment but not yet systematically researched. A state-of-the-art numerical tool will be established to aid material selection and new material design for CFRPs that are to be applied under marine or other harsh conditions.

2. To understand electrochemistry erosion of metal components assembled with CFRP parts because such erosion will significantly impair performance of machines under seawater immersion. Underlying principles about this electrochemistry erosion will be obtained to guide construction of CFRP part joints and selection of component materials for water-involved applications.

3. To create a flexible numerical tool that can customize blade design. Blades need to be built differently as their working conditions change, but currently there is no one-for-all approach for blade design. By applying the proposed modeling method, optimal blades with highest performance-to-cost ratios can be obtained, which will boost utilization of offshore wind turbines to generate clean renewable electricity. In addition, this modeling method can also guide blade damage monitor to improve inspection and maintenance efficiency.

WORK IN PROGRESS

ENERGY MANAGEMENT SYSTEM FOR LARGE-SCALE ELECTRIC VEHICLE CHARGING WITH RENEWABLE GENERATION AND ENERGY STORAGE

Principal Investigator: Professor Yunjian XU
Department of Mechanical & Automation Engineering
CUHK

Research Team Members: Dr. Jin Jiangliang [(1)]

[(1)] Dept. of Mechanical and Automation Engineering

Reporting Period: 01 July 2019 – 30 April 2020

INNOVATION AND PRACTICAL SIGNIFICANCE:

Hong Kong has more than 11,000 plug-in EVs in late July 2017. Many major countries, including the U.S. and China, have witnessed fast-growing adoption of plug-in EVs and intermittent renewable generation. The intermittency and stochasticity of renewable generation (from solar and wind) impose significant challenges on the real-time supply-demand balance of electric power system operation. The key innovation of the proposed project is two-fold: i) a stochastic optimal control based computational approach that optimally schedules the charging of a large number of EVs by explicitly taking into account the stochasticity in future renewable generation, EV arrivals, and electricity prices, and ii) a hardware-in-the loop (HIL) simulator that demonstrates the advantages of the developed energy management system (over existing technical approaches) with actual hardware components simulating real-world power system conditions. The developed HIL demonstrator will facilitate the technology transfer and follow-up funding applications for the potential commercialization of our research results on the cost-minimizing coordinated charging of a large number of EVs for a power distribution system with significant renewable generation.

ABSTRACT

This project aims to develop an energy management system for electric vehicle (EV) charging stations equipped with an energy storage system (e.g., reused EV batteries) and distributed renewable generation (e.g., rooftop solar and small-scale wind generation). The quickly growing adoption of EVs and intermittent renewable generation will impose significant challenges on the secure and efficient operation of electric power systems. We will develop a novel approach (that combines the advantages of stochastic optimal control techniques and data-driven approaches) to harness the inherent flexibility in (deferrable) EV charging load for renewable generation integration and operational cost reduction. Success of the proposed research would maximize the economic and environmental benefits of EV adoption for Hong Kong.

This project will develop i) a software package that optimally coordinates the charging of a large number of (up to 1000) EVs and the operation of an energy storage system to minimize the long-term expected system cost, under random renewable generation, EV arrivals, and electricity prices, and ii) a hardware-in-the loop (HIL) demonstrator that implements and tests the developed computational approaches and power electronic controllers in a realistic hardware environment simulating real-world EV charging station and power distribution system conditions.

1. OBJECTIVES AND SIGNIFICANCE

1. Develop scalable algorithmic approaches to compute the optimal scheduling policies for up to 1000 EV chargers and an energy storage system with intermittent renewable generation.

2. Develop a software module that trains and updates probabilistic models describing future renewable generation and EV arrivals with real-world data.

3. Develop a software package for real-time decision making on the charging of (up to 1000) EVs, based on the updated probabilistic information about future renewable generation and EV arrivals.

4. Implement the developed software package in a hardware-in-the-loop (HIL) simulation platform that verifies the performance of the developed energy management system with actual hardware components in real-world power distribution system environment.

Hong Kong has more than 11,000 plug-in EVs in late July 2017. Many major countries, including the U.S. and China, have witnessed fast-growing adoption of plug-in EVs and intermittent renewable generation. The intermittency and stochasticity of renewable generation (from solar and wind) impose significant challenges on the real-time supply-demand balance of electric power system operation. The key innovation of the proposed project is two-fold: i) a stochastic optimal control based computational approach that optimally schedules the charging of a large number of EVs by explicitly taking into account the stochasticity in future renewable generation, EV arrivals, and electricity prices, and ii) a hardware-in-the loop (HIL) simulator that demonstrates the advantages of the developed energy management system (over existing technical approaches) with actual hardware components simulating real-world power system conditions. The developed HIL demonstrator will facilitate the technology transfer and follow-up funding applications for the potential commercialization of our research results on the cost-minimizing coordinated charging of a large number of EVs for a power distribution system with significant renewable generation.

2. RESEARCH METHODOLOGY

Through a stochastic optimal control formulation, we seek to fully characterize a policy that optimally coordinate the charging of a large number of EVs and energy storage operation so as to minimize the (daily or weekly) expected operational costs of EV charging stations (including electricity cost and penalty cost for not fulfilling EVs' charging demands). Based on the optimal policy characterizations, we will develop and implement scalable computational approaches in a software package making real-time optimal decisions under random EV arrivals, renewable generation, and electricity prices. We will build a hardware-in-the-loop (HIL) demonstrator that simulates the performance of the developed energy management system in the actual hardware environment of an EV charging station equipped with solar PV generation and energy storage systems.

3. RESULTS ACHIEVED SO FAR

This project focuses on the joint scheduling of EV charging and energy storage devices under random renewable generation and electricity prices. In the past 9 months, we have established structural characterizations of optimal policies, and developed efficient algorithms to compute the optimal scheduling policies with real-world data inputs, for two different application scenarios with constant and adjustable EV charging power.

1) For the case with constant (non-adjustable) charging power, the decision on EV's charging is binary. We formulate the scheduling problem as a restless multi-armed bandit (RMAB) problem.

Relaxing the scheduling problem into multiple independent single-arm scheduling problems, we define the Lagrangian priority value as the greatest tax under which it is optimal to activate the arm. We propose a Lagrangian priority policy which processes EVs in the order of their Lagrangian priority values, and establish its asymptotic optimality as the system scales. Numerical results on real-world data show that the proposed Lagrangian priority policy achieves 22%-49% higher average reward than the classical Whittle index policy.

These results will be published at the flagship journal in the field of automatic control [J1].

2) For the case with constant (non-adjustable) charging power, we have further considered the joint scheduling of EV charging load and energy storage devices under random renewable generation and electricity prices [J3]. We establish an index based priority rule that is shown to be optimal under arbitrary system dynamics: tasks with less laxity should be processed first, and for two tasks with the same laxity, the task with a later deadline should have the priority. Based on the established optimal control policy characterizations, we propose to apply deep reinforcement learning (RL) methods to compute the total charging power (to all EVs). Numerical results on real-world data show that the proposed approach significantly outperforms existing RL methods combined with the earliest deadline first (EDF) priority rule (by reducing 46-53% of system cost).

These results will be published at the flagship journal in the field of automatic control [J3].

3) For the case with adjustable charging power, the decision on EV's charging is in a continuous action space. We formulate the cost-minimizing scheduling problem faced by an EV charging station operator as a dynamic program. When the number of EVs is large, the formulated dynamic program cannot be exactly solved by brute-force methods due to the curse of dimensionality. We show that given the total amount of energy charged into all EVs, the optimal energy allocation (among EVs) follows a threshold policy, which attempts to charge/discharge all EVs' battery to a target State-of-Charge (SoC), which enables the development of scalable computational approaches. The proposed approach achieves close-to-optimal performance in numerical experiments with real-world electricity pricing and solar generation data.

These results will be published at the flagship journal in the field of automatic control [J4].

To sum up, we have achieved the first three objectives listed in the proposal (see Section 1 of this report). In particular, we have developed a software module that trains and updates probabilistic models describing future renewable generation and EV arrivals with real-world data via deep neural networks. With the developed software module, we have developed scalable algorithms that can compute the optimal scheduling policies for 1000 EV chargers and an energy storage system with random renewable generation and electricity prices, for both cases with constant and adjustable EV charging power. Compared with the state-of-the-art (online optimization and reinforcement learning) approaches, the developed algorithmic approach has demonstrated significant improvement in both learning speed and system cost reduction.

In the next 14 months, based on the established theoretic and algorithmic results, we will develop a hardware-in-the-loop (HIL) simulation platform that implements the developed software package and verifies its performance of the developed energy management system with actual hardware components in real-world power distribution system environment.

Benchmarking the performance of the developed energy management system with actual hardware components in real-world power distribution system conditions, the HIL demonstrator will facilitate

the technology transfer and follow-up funding applications for the potential commercialization of our research results.

4. PUBLICATION AND AWARDS

J[1] L. Hao, Y. Xu*, and L. Tong, "Asymptotically optimal index policies for deadline scheduling with processing rate limits," conditionally accepted to *IEEE Trans. on Automatic Control*, IEEE, 2020.

J[2] J. Jin and Y. Xu*, "Segregated linear decision rules for distributionally robust control with linear dynamics and quadratic cost," accepted to *IEEE Systems Journal*, IEEE, 2020.

J[3] J. Jin and Y. Xu*, "Joint Scheduling of Deferrable Demand and Storage with Random Supply and Processing Rate Limits," conditionally accepted to *IEEE Trans. on Automatic Control*, IEEE, 2020.

J[4] J. Jin, Y. Xu*, and Z. Yang, "Optimal deadline scheduling for electric vehicle charging with energy storage and random supply," accepted to *Automatica*, 2020.

C[1] L. Hao and Y. Xu*, "Index Policies for Stochastic Deadline Scheduling with Time-varying Processing Rate Limits," *American Control Conference*, Denver, CO, USA, July 1-3, 2020.

WORK IN PROGRESS

DEVELOPMENT OF A NOVEL COOLING TOWER WITH FREE DAYTIME RADIATIVE COOLING FOR REDUCING ENERGY CONSUMPTION IN BUILDINGS

Principal Investigator: Professor CHEN Chun
Department of Mechanical & Automation Engineering
CUHK

Research Team Members:
Xinxian Yu, Ph.D. Student [(1)],
Haiqiang Zhang, Research Assistant [(1)]

[(1)] Dept. of Mechanical and Automation Engineering

Reporting Period: 01 July 2018– 30 April 2019
(to be completed in June 2020)

INNOVATION AND PRACTICAL SIGNIFICANCE:

Conventional cooling towers drag the outdoor air to cool the cooling water for rejecting heat to the atmosphere. Lower cooling water temperature results in a higher COP of chillers. Therefore, it is worthwhile to enhance the heat rejection in cooling towers without consuming additional energy. The innovation of this work is to develop a cooling tower with free daytime radiative cooling. The proposed cooling tower utilizes free and renewable cooling to lower the cooling water temperature. Consequently, the COP of chillers is expected to increase by 10 to 20%. A prototype will be fabricated and tested in this project. With the collaboration with the heating, ventilation, and air-conditioning (HVAC) industry, we will actively see further development of the prototype and potential technology transfer. If successful, the novel cooling towers can be potentially used in commercial and residential buildings to reduce the energy consumption and the associated carbon dioxide emissions.

ABSTRACT

The air-conditioning systems in buildings consume about 30% of the total electricity in Hong Kong. In a typical heating, ventilation, and air-conditioning (HVAC) system, the conventional cooling tower drags the outdoor air to cool the cooling water for rejecting heat to the atmosphere. To reduce the energy consumption, this project proposed to develop a novel cooling tower with renewable sky radiative cooling. A basin coated with a film of radiative cooling metamaterial, as a sky radiative cooler, will be implemented into the cooling tower. The film can reflect the solar irradiance and draw the heat from the water through the infrared transparency window of the atmosphere to the cold sink of outer space. The radiative cooling is free and renewable because the cold sink of outer space can be effectively regarded as a cooling reservoir. Consequently, the cooling water temperature will decrease without consuming additional energy, so that the coefficient of performance (COP) of chillers will increase. The design of the proposed cooling tower will be supported by thermodynamic modeling. Experiments will be conducted to evaluate the performance of the sky radiative cooler. The proposed project will offer a novel cooling tower that can utilize renewable cooling and reduce the energy consumption in buildings.

1. OBJECTIVES AND SIGNIFICANCE

1.1. Objectives

The first objective is to propose a novel cooling tower with renewable sky radiative cooling. The proposed cooling tower will utilize sky radiative cooling to reduce the condenser temperature, so that the COP of the chillers can be increased. Thus, the new system can be potentially applied in buildings to reduce the energy consumption.

The second objective is to develop a numerical thermodynamic model for predicting the performance of the cooling tower with renewable sky radiative cooling. The developed model will be used to support the design of the cooling tower to achieve the optimal energy performance.

The third objective is to evaluate the system performance under various working conditions using the numerical model. This work can identify the key influencing factors on the energy performance and propose the suitable application working environment of the cooling tower with sky radiative cooling.

The fourth objective is to fabricate a sky radiative cooler and conduct experimental measurements of the cooling capacity under various conditions. The obtained experimental data can be used to support and verify the design of cooling tower with sky radiative cooling.

1.2. Significance of this project

Conventional HVAC cooling towers drag the outdoor air to cool the cooling water for rejecting heat to the atmosphere. Lower cooling water temperature results in a higher COP of chillers. Therefore, it is worthwhile to enhance the heat rejection in cooling towers without consuming additional energy. The innovation of this work is to develop a cooling tower with renewable sky radiative cooling. The proposed cooling tower utilizes free and renewable sky radiative cooling to lower the cooling water temperature. Consequently, the COP of chillers is expected to increase by 5 to 10%. A prototype sky radiative cooler will be fabricated and tested in this project. With the collaboration with the HVAC industry, we will actively see further development of the prototype and potential technology transfer. If successful, the novel cooling tower with sky radiative cooling can be potentially used in commercial and residential buildings to reduce the energy consumption and the associated carbon dioxide emissions.

2. RESEARCH METHODOLOGY

2.1 Cooling tower with sky radiative cooling

This study proposed to implement a passive sky radiative cooler between the cooling tower and the condenser. Figure 1 shows a schematic of the system setup. This investigation focused on a counterflow cooling tower without the fan speed control. The high-temperature cooling water from the condenser entered into the cooling tower, and the spray water droplets had heat and mass transfer with the included air. The water leaved the cooling tower with a lowest possible temperature of the outdoor wet-bulb temperature. The cool temperature then entered into a radiative cooler, which consisted of a basin covered by a metamaterial film with radiative materials. Through radiative heat transfer to the outer space, the cooling water was further cooled before flowing back to the condenser. Through this process, the condenser temperature was decreased, so that the COP of chiller could be improved.

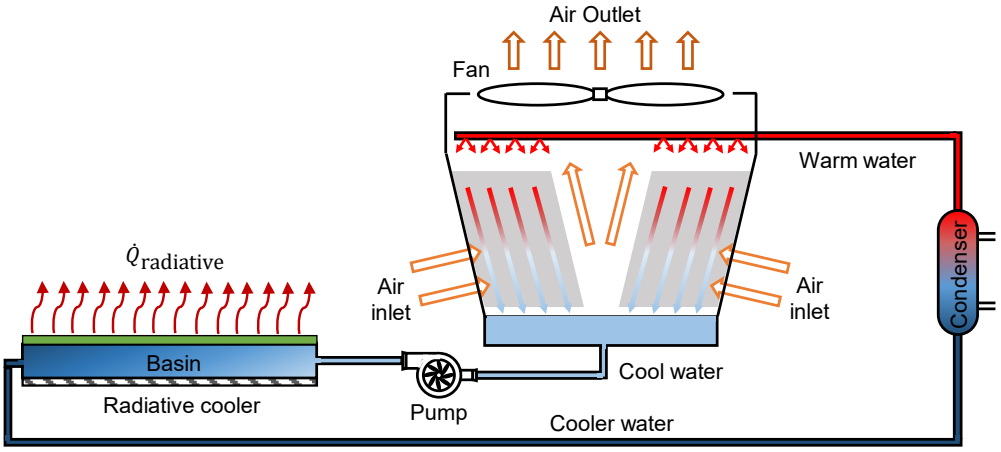


Figure 1. Schematic of the proposed cooling tower with renewable passive radiative cooling.

Figure 2 shows the schematic of the metamaterial film with radiative materials. The upper layer can reject heat through the infrared irradiance to the cold sink of outer space. The radiative material has strong emission between 8 and 13 μm, the atmospheric transmission window. The lower layer can reflect the solar irradiance so that the radiative cooler can still work in the daytime. With the use of the radiative cooler, the system may achieve a cooling water temperature lower than outdoor wet-bulb temperature. However, it is still unknown if the proposed cooling tower with passive sky radiative cooling could actually improve the COP of chiller. Therefore, this study will develop a numerical model for the analysis in the following section.

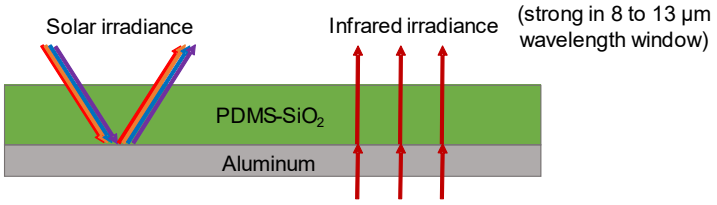


Figure 2. Schematic of the metamaterial film that can reflect the solar irradiance and reject heat through the infrared irradiance to the cold sink of outer space.

2.2 Mathematical model

Considering the steady-state condition, the radiative emission power of the cooler is equal to the net incident power absorbed by the cooler:

$$2\pi A_{rc,a}\int_0^{\pi/2}\sin\theta\cos\theta\int_0^{\infty} I_{BB}(T_{rc},\lambda)\varepsilon_{rc}(\lambda,\theta)d\lambda d\theta = A_{rc,a}\int_0^{\infty} I_{AM1.5}\varepsilon_{rc}(\lambda)d\lambda$$
$$+2\pi A_{rc,a}\int_0^{\pi/2}\sin\theta\cos\theta\int_0^{\infty} I_{BB}(T_{atm},\lambda)\varepsilon_{rc}(\lambda,\theta)\varepsilon_{atm}(\lambda,\theta)d\lambda d\theta + A_{rc,a}h_{rc,a}(T_{atm}-T_{rc}) + m_w c_{p,w}(T_{w2}-T_{w1}) \quad (1)$$

where A_{rc} (m^2) is the cooling surface area exposed to the sky, θ (sr) is the radiation angle, I_{BB} ($W/m^2 \cdot sr \cdot m$) is the spectral radiance of a blackbody, T_{rc} (K) is the temperature of the radiative cooler, ε_{rc} (unitless) is the emissivity of the radiative cooling material, $I_{AIM1.5}$ ($W/m^2 \cdot m$) is the solar illumination, T_{atm} (K) is the temperature of the ambient air, $\delta_{w,atm}$ (atm-cm) is the absolute vertical water vapor column in the atmosphere, ε_{atm} (unitless) is the emissivity of the atmosphere, $h_{rc,a}$ ($W/m^2 \cdot K$) is the convective heat transfer coefficient between the cooler and the surrounding air, T_{w1} (K) is the temperature of the water entering the radiative cooler (or leaving the cooling tower), and T_{w2} (K) is the temperature of the water leaving the radiative cooler (or entering the condenser). The spectral radiance of a blackbody can be calculated by

$$I_{BB}(T,\lambda)=\frac{2hc^2}{\lambda^5}\frac{1}{\exp(\frac{hc}{\lambda k_B T})-1}$$

(2)

where h is the Planck's constant (6.626×10^{-34} J·s), c is the speed of light (2.998×10^{8} m/s), λ (m) is the wavelength, and k_B is the Boltzmann constant (1.381×10^{-23} $m^2\cdot kg/s^2\cdot K$). The emissivity of the atmosphere, which can be calculated based on the "box model" proposed by Granqvist and Hjortsberg:

$$\varepsilon_{atm}(\lambda,\theta)=\begin{cases}1 & \lambda<8\ \mu m\\ 1-t(\lambda,\delta_{w,atm})^{1/\cos\theta} & 8\ \mu m\le\lambda\le13\ \mu m\\ 1 & \lambda>13\ \mu m\end{cases}$$

(3)

where t (unitless) is the atmospheric transmittance, which can be calculated using the software MODTRAN.

This study focused on counterflow cooling tower with a constant fan speed. Based on the cooling tower theory proposed by Merkel, the heat and mass transfer process occurs between water, interfacial film, and air. The interfacial film was assumed to be of saturated air. Under steady-state condition, the water heat loss is equal to the air heat gain:

$$m_w c_{p,w} dT_w = m_a dh_a = K\alpha(h_{film}-h_a)dV \Rightarrow \frac{K\alpha V}{m_w}=\int_{T_{w1}}^{T_{w3}}\frac{c_{p,w}}{h_{film}-h_a}dT_w$$

(4)

where m_w (kg/s) is the inlet water mass flow rate, $c_{p,w}$ (kJ/kg·K) is the specific heat of water, T_w (K) is the water temperature, m_a (kg/s) is the air mass flow rate, h_a (kJ/kg) the enthalpy of bulk air, K ($kg/s\cdot m^2$) is the unit conductance of mass transfer from the water-air interface to main airstream, α (m^2/m^3) is the ratio of water-air interface area to the cooling tower volume, h_{film} (kJ/kg) is the enthalpy of saturated air at the bulk water temperature, V (m^3) is the cooling volume of the tower, and T_{w3} (K) is the temperature of water leaving the cooling tower (or entering the radiative cooler).

The COP of the chiller can be calculated by:

$$COP=\frac{Q_{evap}}{m_w c_{p,w}(T_{w,3}-T_{w,2})-Q_{evap}}=\frac{T_{evap}}{\beta_1\cdot T_{w,3}+\beta_2-T_{evap}}\eta$$

(5)

where Q_{evap} (W) is the heat absorbed by the evaporator, T_{evap} (K) is the average temperature of evaporator, T_{cond} (K) is the average temperature in condenser, β_1 and β_2 are constants, and η (unitless) is the internal efficiency of the chiller. Solving the equations above, the temperatures, including T_{rc}, T_{w1}, T_{w2}, T_{w3}, and T_{cond}, can be obtained.

3. RESULTS ACHIEVED SO FAR

This study used the developed numerical model to predict the improvement in COP of chiller and reduction in chiller electricity use for several buildings. The outdoor air temperature and relative humidity were set the monthly average values in Hong Kong for a whole year. The cooling load per unit floor area was set at 60 W/m^2. The rooftop area available for the sky radiative cooler was assumed to be 80%. The cooling tower volume and water flow rate were set at the average value from the data collected from the literature. The K·α

was set at 0.445 according to the U.S. Department of Energy (DOE) report. The radiative cooler material was selected to be of high emissivity in the wavelength range of 8 to 13 μm, while very low emissivity in other wavelength ranges. Figure 3 plots the percentage of reduction in chiller electricity use and increase in chiller COP for the buildings with different numbers of floor. When the number of floor increased, the corresponding cooling load increased, so that the cooling water flow rate tended to increase. In that case, with the same sky radiative cooling area, the reduction in cooling water temperature decreased. Thus, the cooling tower with sky radiative cooling performed better for lower floor buildings. Although the results show significant reduction in chiller electricity use, more parametric studies are needed in the second year of this project.

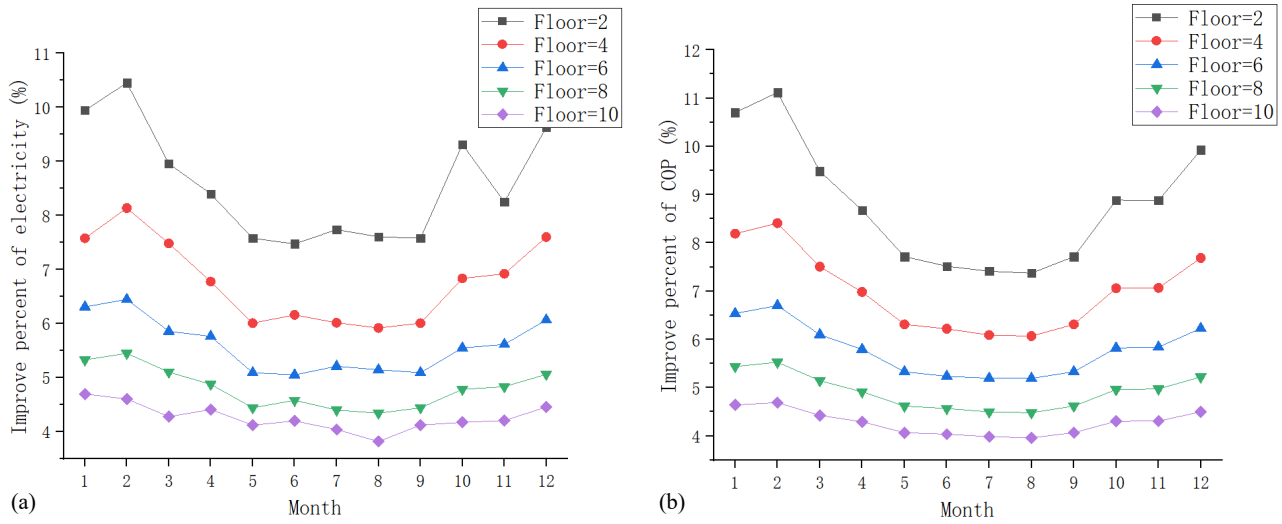


Figure 3. (a) Percentage of reduction in chiller electricity use, and (b) percentage of increase in chiller COP.

A preliminary experiment has also been carried out. The fabricated sky radiative cooler consisted of a water tank covered by a sky radiative cooling material film. In the second year of this project, a water flow loop with a controllable heater will be added to the radiative cooler to simulate the cooling water circuit. More experiments will be conducted to obtain data to support the design of the cooling tower with sky radiative cooling.

4. PUBLICATION AND AWARDS

J[1] X. Yu, H. Zhang, and C. Chen, "Numerical model of the performance of HVAC cooling tower with passive sky radiative cooling," *Energy Conservation and Management*, under preparation.

WORK IN PROGRESS

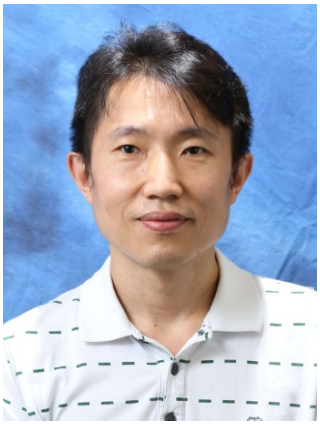
MEGAHERTZ CURRENT SENSOR FOR MEGAHERTZ RENEWABLE ENERGY CONVERTER

Principal Investigator: Professor LOH Poh Chiang Andrew
Department of Electronic Engineering, CUHK

Co-Investigator: XIN Zhen [(1)]

Research Team Members: MING Lei, Ph.D. Student [(1)]

[(1)] Department of Electronic Engineering, CUHK



Reporting Period: 01 July 2018– 30 April 2019
(to be completed in June 2020)

INNOVATION AND PRACTICAL SIGNIFICANCE:

The developed current sensor will have a frequency bandwidth up to 10 megahertz. It is thus around 40 times wider than that of a commonly used Hall current sensor. Such wide bandwidth permits the realization of fast control and reliable protection in the newest generation of power converters built using WBG devices. The resulting converters can be sized for renewable energy generation or miniaturized for routinely used laptop adapter, EV charger and phone charger to name only a few. There will be a revolutionary reduction of size and weight, enabled by the high-frequency operation of WBG devices. In addition, the developed sensor is of great commercial competitiveness due to its small size and low cost, made possible by its integration into an inexpensive printed circuit board. This merit will promote the coming era of WBG devices with extremely high efficiency, but has its commercialization hindered many years due to its high price. Moreover, the substantial market volume and the all-important cost factor have led to the development of a wide range of alternative current sensing methods. The market demand for isolated current sensors will, in fact, hit 100 million in 2020. This is roughly equivalent to the amount of iPhones produced in 2012 [1]. Therefore, the developed current sensor is revolutionary, yet with great potential and competitiveness to be converted into a commercial product.

ABSTRACT

Power converter is an essential interface for tying a renewable source (e.g. solar and wind) to the power system. It usually consists of three main components, respectively known as microprocessor, power semiconductor devices and sensors. If its microprocessor is then analogously viewed as its “brain”, its sensors and power devices are then its “sense organs” and “limbs”, respectively. Recently, technological progress has pushed operational speed of its “brain” to the ***gigahertz*** range, while the development of wide bandgap (WBG) devices has allowed its “limbs” to reach the ***megahertz*** range with both high efficiency and power density (power per unit volume). The next trend of rapid development will hence likely be related to its “sense organs”, or more precisely, its current sensors, presently limited to below hundreds of ***kilohertz***. The ***megahertz*** responses of the “limbs” are thus not sensed properly for control, protection and monitoring of the power converter. These are nontrivial issues, judging from the amount of power generated by a typical renewable source. An intense need for advanced current sensing techniques that can sense from DC to a few ***megahertz*** with both high noise immunity and low manufacturing cost is thus prevailing, but presently cannot be met by existing commercial sensors. Development of an advanced current sensor is thus timely, albeit challenging.

1. OBJECTIVES AND SIGNIFICANCE

The developed current sensor must have the following objective features, which upon materialized, will fasten the era of highly efficient WBG usage in miniaturized power converters. Possible applications include renewable energy generation, laptop / phone adapter, and electric vehicle charger to name only a few. Its commercialization has however been hindered by high component prices, including that of the current sensor, whose market demand will likely reach 100 million in 2020. This is roughly the number of iPhones produced in 2012. Therefore, the developed current sensor is revolutionary with great potential as a commercial product.

Ultrafast with a bandwidth up to 10 MHz: WBG devices can operate at an extremely high frequency (up to megahertz), which in essence, is the key towards realization of high-efficiency and high-power-density renewable energy generation. But, in terms of their short-circuit protection, operating current measurement becomes a significant challenge, which practically, cannot be achieved with the widely used Hall current sensors due to their limited 250-kHz bandwidth. A megahertz current sensor is thus essential.

Nonintrusive with a very low insertion inductance of less than 1nH: High-speed WBG power devices are highly sensitive to parasitic inductances, which in the extreme, can downgrade their performances towards those of silicon devices. Therefore, very low insertion parasitic, especially inductance, is necessary.

Compact with the target of embedding within highly dense power converter: High power density has always been the packaging target of power converters, in order to fully utilize energy resources and lessen operating costs. It has to date roughly doubled every 10 years since 1970, but can now be impeded by existing bulky current sensors. For instance, recent photovoltaic inverter invented through the Google Little Box Challenge has achieved a 2-kW power rating with its volume being the same as two iPhone5s. Further reduction of its size is however not easy, since it depends on the current sensor, which presently is larger than an Apple watch. Development of newer current sensors is thus an immediate challenge to resolve.

Low cost: Instead of explicitly mounting a (e.g. hall-effect) current sensor, it is conceptually cheaper to have the current sensor embedded within the print-circuit board (PCB), in addition to saving some footprints. Development of such PCB-embedded current sensors is thus the main research concern of this project.

2. RESEARCH METHODOLOGY

The project consists of a number of tasks to be investigated by a postdoctoral fellow. Its core task is to find solutions that can enormously reduce volume of the conventional PCB Rogowski current sensor (RCS). Despite that, the resulting RCS must simultaneously retain its wide bandwidth and ability to work in a hostile environment, characterized by large voltage transients and high field strength. To achieve these goals, the methodology followed is described as follows.

2.1. Structural Design and Layout of Sensor Head and Coil

Performance of a RCS is closely related to the number of coil turns. On one hand, high number of turns is desirable, since it increases measurement accuracy due to the existence of a high mutual inductance. On the other hand, with increasing number of turns, self-inductance of the coil increases faster than its mutual inductance, which in response, can cause the coil resonance frequency and bandwidth to drop. This problem becomes more challenging with the proposed tiny RCS due to its extremely limited size and volume close to those of a coin. Tradeoff between dynamics and accuracy of the developed sensor must hence be carefully investigated when designing structures of the sensor head and coil.

2.2. Development of Techniques for shielding Electrostatic Interferences

Power converters, such as micro-photovoltaic inverters, are shrinking in size, even though their power ratings are rising. Smaller volumes then create a more hostile environment for the current sensors, because of

the increased electrostatic interferences. The condition worsens with WBG devices operating at much faster switching speeds than conventional devices. Immunity, related to rejection of external fields, of the developed PCB RCS must hence be improved, before different currents flowing within the power converter can be measured accurately. Fitting a shield over the coil windings is a common solution for conventional Rogowski coils, but becomes inappropriate with a power converter, since the shield will substantially reduce bandwidth of the sensor. Therefore, an alternative cost-effective solution for rejecting external fields is investigated.

2.3. Identification of Parametric Design Rules

Accurate design rules for choosing components of the developed RCS is necessary, before commercialization and mass production. An equivalent model of the Rogowski coil must hence be developed for that purpose and its theoretical performance evaluation. A final design procedure can eventually be formulated for sizing parameters of the optimized Rogowski coil.

2.4. Inclusion of DC Current Measurement to Rogowski Current Sensor

The key disadvantage of a Rogowski coil is its inability to detect DC current. This hinders its application to certain power converters, whose DC currents may sometimes be essential for both control and protection. A recent hybrid sensing solution that combines Rogowski and anisotropic magneto resistive (AMR) techniques has thus been developed to address that shortcoming. The idea is to rely on AMR for sensing DC and low-frequency current components and a Rogowski coil for measuring high-frequency current components. This solution however suffers from high cost and design difficulty. An alternative technique that uses multiple Rogowski coils to harness switching characteristics of a power converter for DC current measurement is thus suggested for investigation in the project.

2.5. Experimental Test-Bed and Performance Evaluation

Performances of the developed PCB RCS, in terms of its external field rejection, DC current measurement and other characteristics, will be evaluated sequentially using a double-pulse testbed throughout the course of investigation. To demonstrate even more realistically, overall performances of the final sensor prototype will also be tested with a high-power-density power converter to be built in the laboratory. More precisely, the developed current sensor will be integrated within the power converter for short-circuit protection and current control. Its performance accuracy will then be compared with other existing current sensors.

3. RESULTS ACHIEVED SO FAR

A four-layer screen-returned printed-circuit-board (PCB) Rogowski current sensor (RCS) has been developed for measuring fast-changing current of a WBG device with virtually no interference from ambient noises. It uses lesser PCB layers than existing sensors to save costs and much fewer turns for its Rogowski coil to retain its high bandwidth and small size. The latter is however at the expense of more leakage between turns. This causes its self-inductance, needed for designing its bandwidth, to be even more difficult to compute accurately using traditional techniques. Errors as high as 45% have, in fact, been reported in the literature. A piecewise PCB technique has hence been proposed, whose error has been found to be smaller than 5%, if the coil pitch is ten times larger than its track width. For cascading with the Rogowski coil, an appropriate non-inverting integrator has also been implemented for accurately regenerating the measured switch current without being burdened by excessive shortcomings of a traditional integrator. Overall effectiveness of the proposed RCS has eventually been verified experimentally using a double-pulse test setup and a coil with twenty turns. A photograph showing the designed RCS can be viewed from Fig. 1, together with an illustration of how close its measured current i_{SC} tracks the actual current i'_{SC}.

For demonstrating next that self-inductance determination for the Rogowski coil is indeed accurate, Table I can be referred to. The table clearly shows that with the proposed piecewise technique, calculation error is very small, and in fact, becomes smaller as the number of turns decreases. This trend can be explained by recapping that the piecewise technique is proposed to better manage leakage fluxes between adjacent turns of

the coil. Leakage fluxes, in turn, worsen as the number of turns decreases. In other words, the proposed technique will become more accurate as the number of turns drops. In contrast, the compared existing technique relies on a toroidal model, whose leakage flux accountability is very poor. Its calculation error is thus big and will become bigger as the number of turns decreases.

To lastly demonstrate the existence and severity of leakage fluxes, Fig. 2 shows two longitudinal PCB coils with thirty and five turns, respectively. Their finite-element flux distributions analyzed with JMAG are also shown in the same figure. Clearly, with more turns in Fig. 2(a), a vast amount of mutual fluxes links many turns of the coil, even though some leakage fluxes closer to the coil still exist. The distribution however becomes very different in Fig. 2(b), where fewer turns produce mostly leakage fluxes. In other words, the neat mutual flux linking pattern in Fig. 2(a) can no longer be seen. Existing toroidal method for computing self-inductance will hence work fine with Fig. 2(a), while the proposed piecewise method will give more accurate results with Fig. 2(b).

Table I. Measured and Computed Self-Inductances

Turn Number	Pitch (mm)	Measurement (nH) at 1MHz	Existing Method		Proposed Method	
			Theory (nH)	**Error (%)**	Theory (nH)	**Error (%)**
N = 30	1.3	281.19	187.00	**33.50**	230.22	**18.13**
N = 20	2.0	168.53	83.11	**50.68**	160.14	**4.97**
N = 10	3.9	93.85	20.78	**77.86**	92.97	**0.95**

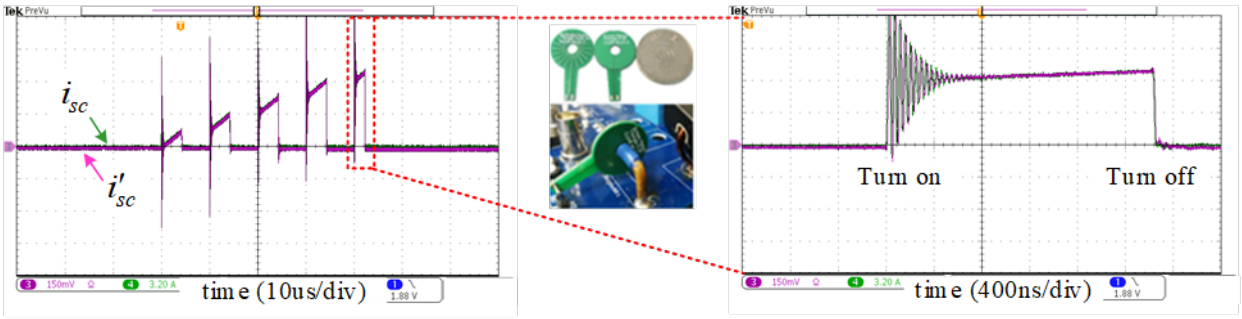
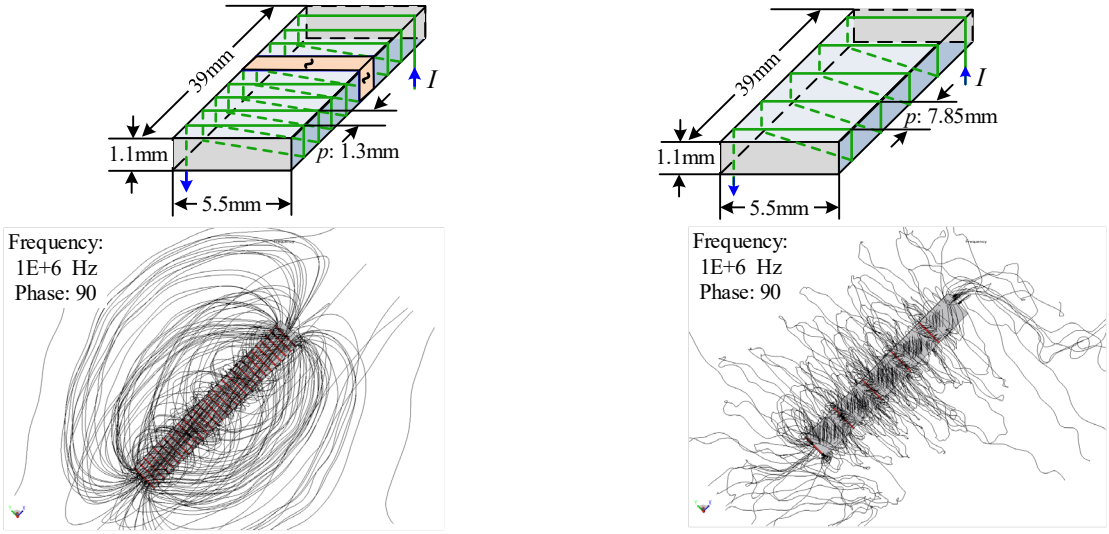


Fig. 1. Illustration of measured current following actual current accurately (actual current measured with Tektronix TCP0030A current probe with a bandwidth of 120MHz).



(a)
(b)

Fig. 2. Structures and longitudinal magnetic field distributions of (a) thirty-turn and (b) five-turn PCB coils.

4. PUBLICATION AND AWARDS

C[1] L. Ming, C.Q. Yin, Z. Xin, P.C. Loh, and Y. Liu, “Screen-Returned PCB Rogowski Coil for Switch Current Measurement of SiC Devices,” *IEEE Applied Power Electronics Conference and Exposition (APEC)*, IEEE, Anaheim, California, USA, pp. 958-964, March 17-21, 2019

WORK IN PROGRESS

DEVELOPMENT OF HIGH-PERFORMANCE TRIBOELECTRIC NANOGENERATORS FOR RENEWABLE BLUE ENERGY HARVESTING

Principal Investigator: Professor ZI Yunlong
Department of Mechanical & Automation Engineering
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Research Team Members:
Ms. Jingjing Fu[(1)], Dr. Yubiao Sun[(1)], Dr. Xiaoyi Li[(1)], Dr. Jiaqi Wang[(1)]

[(1)] Department of Mechanical and Automation Engineering, CUHK

Reporting Period: 01 July 2018– 30 April 2019
(to be completed in June 2020)

INNOVATION AND PRACTICAL SIGNIFICANCE:

Innovation: *The innovation of the proposed research lies in the development of high-performance TENGs for blue energy harvesting. Traditional water energy harvesting uses electromagnetic generators (EMG), which are usually huge, heavy, expensive, and technically difficult for construction in deep water. Further, studies have demonstrated that EMG are extremely inefficient in harvesting the low-frequency mechanical energy that is generated by ocean waves. TENG possess several advantages over EMG technology as they are lightweight and able to float, cost-effective and easy to produce, and efficient in harvesting low-frequency energy. Our research will focus on maximizing TENG output through addressing two crucial fundamental issues: the air-breakdown effect inside TENG and the parasitic capacitances brought by seawater, which have never been systematically studied before. For the first time, we propose to develop TENGs with novel designs to address these issues. It is expected that the output performance of TENG could increase 10-100 times through our proposed research.*

Practical significance: *Considering the challenges of energy security and environmental protection, developing renewable energy sources is of critical importance for Hong Kong. With Hong Kong's extensive coastline and water area percentage of 59.8%, Hong Kong is strategically placed to take advantage of a convenient, clean and renewable power source. Especially for areas with complex coastlines that are not suitable for water shipping, electrical generation is the best option to utilize them. Additionally, the ocean currents and tropical storms that are common in Hong Kong, provide an abundant amount of mechanical energy that could potentially be converted to electrical energy. Lastly, developing the blue energy harvesting technology to replace the fossil fuels will also decrease the emissions of pollutants and greenhouse gases, which is critical for environmental protection. Therefore, developing blue energy harvesting through TENG is beneficial to Honk Kong on many levels including the mediating the energy crisis, promoting environmental protection, and advancing both economic and social development in Hong Kong.*

ABSTRACT

Electricity is the world's fastest growing form of end-use energy consumption. Between 2015 and 2040, world net electricity generation will increase by 45%. Non-renewable fossil fuels still account for >60% of electricity generation. However, 70% of the earth's surface is covered by ocean, which represents a huge

untapped clean and renewable energy source. Estimated to provide power of over 75 TW, ocean energy could satisfy energy demands around the world. To effectively harvest this "blue energy" especially the low-frequency mechanical energy generated by ocean waves, three-dimensional networks of triboelectric nanogenerators (TENG) have been proposed. To test this concept, however, TENG units first need to be refined to optimize their output performance. To date, factors that limit the performance include the challenge that achievable charge density is limited by the phenomenon of air breakdown; additionally, the parasitic capacitances brought by the conductive seawater may suppress the performance of TENG. We propose experimental and theoretical studies that will focus on mitigating these limiting factors by developing novel structural and material designs, greatly enhancing the output performance of TENG. The proposed research will lay the cornerstone for further technologic advancement in large-scale harvesting of kinetic water energy using TENG units.

1. OBJECTIVES AND SIGNIFICANCE

1.1 Objectives: (1) To simulate and experimentally demonstrate a TENG design that will minimize the air-breakdown effect using controlled high pressure and inert gas environments; (2) To simulate and experimentally develop optimized structural/material designs to minimize the influences of the parasitic capacitances brought by the conductive seawater; (3) To determine the optimized designs and produce a TENG that provides maximal available output, and to compare with other technologies used in blue energy harvesting.

1.2 Significance: Considering the challenges of energy security and environmental protection, developing renewable energy sources is of critical importance for Hong Kong. With Hong Kong's extensive coastline and water area percentage of 59.8%, Hong Kong is strategically placed to take advantage of a convenient, clean and renewable power source. Especially for areas with complex coastlines that are not suitable for water shipping, electrical generation is the best option to utilize them. Additionally, the ocean currents and tropical storms that are common in Hong Kong, provide an abundant amount of mechanical energy that could potentially be converted to electrical energy. Lastly, developing the blue energy harvesting technology to replace the fossil fuels will also decrease the emissions of pollutants and greenhouse gases, which is critical for environmental protection. Therefore, developing blue energy harvesting through TENG is beneficial to Honk Kong on many levels including the mediating the energy crisis, promoting environmental protection, and advancing both economic and social development in Hong Kong.

2. RESEARCH METHODOLOGY

2.1 Theoretical modeling and simulation of water-wave TENG: The basic model of the water-wave TENG is built and simulated by COSMOL Multiphysics, a cross-platform finite element analysis simulation software. It can provide the potential and electric field distribution which can be used to determine the breakdown status and the voltage output. It can also simulate the balanced charge status so that the available charge output can be given.

2.2 Experimental studies on the breakdown and parasitic-capacitance effects: In the measurement circuit as shown in **Fig. 2a**, the charging TENG is used to provide the high voltage required to approach the breakdown conditions in the test TENG. The charge transfer was measured by the electrometer with mark of "Q", and the voltage was calculated by the measured current through the electrometer with mark of "A" multiplying the shunt resistance R. The voltage at the turning points is recorded as the breakdown voltage, and then it was mapped into the V-Q diagram of TENG to outline the breakdown region. A high-speed camera is used to record the sparks during breakdown. In the non-breakdown part of the V-Q plot, the capacitance can be estimated by the slope.

2.2 Fabrication and electrical measurement of water-wave TENG output: A hollow plastic ball was used as the shell. Two copper films were attached to the inner side of the shell. A silicone rubber solid ball was put into the plastic ball to act as the moving part. Water-wave energy was simulated by a linear motor to supply a periodical external force with specified frequency. A pressure sensor was simultaneously placed under the TENG to calibrate the applied force. And the electrical properties of TENGs including output voltage, power, reliability and consistency were investigated by using a digital oscilloscope with a 100 MΩ probe, or a Keithley 6514 electrometer.

2.3 Fabrication of the optimized water-wave TENG design: To fill in the high-pressure CO_2, we designed and fabricated a ball-shell TENG with a screw cap, in which the high-pressure CO_2 gas can be filled and

packaged inside (**Fig. 3a**). Silicone sealing layer is applied after tightening the cap to maintain the high-pressure environment inside. To reduce the parasitic capacitance from the water, we fabricated an additional layer made from packaging foams, with thickness of ~0.5 cm.

2.4 Development of the pressure vessel for quantitative analysis of the environmental factors: A chemical reaction chamber (from Gongyi Yuhua) was modified as a pressure vessel for testing TENG in controlled environments. A low-speed bidirectional motor was installed to provide the driven motion for TENG, and a framework was built inside to support the TENG. The electrodes were connected to the electrometers outside of the vessel through copper wires.

3. RESULTS ACHIEVED SO FAR

3.1 The modeling and simulations of the water-wave TENG

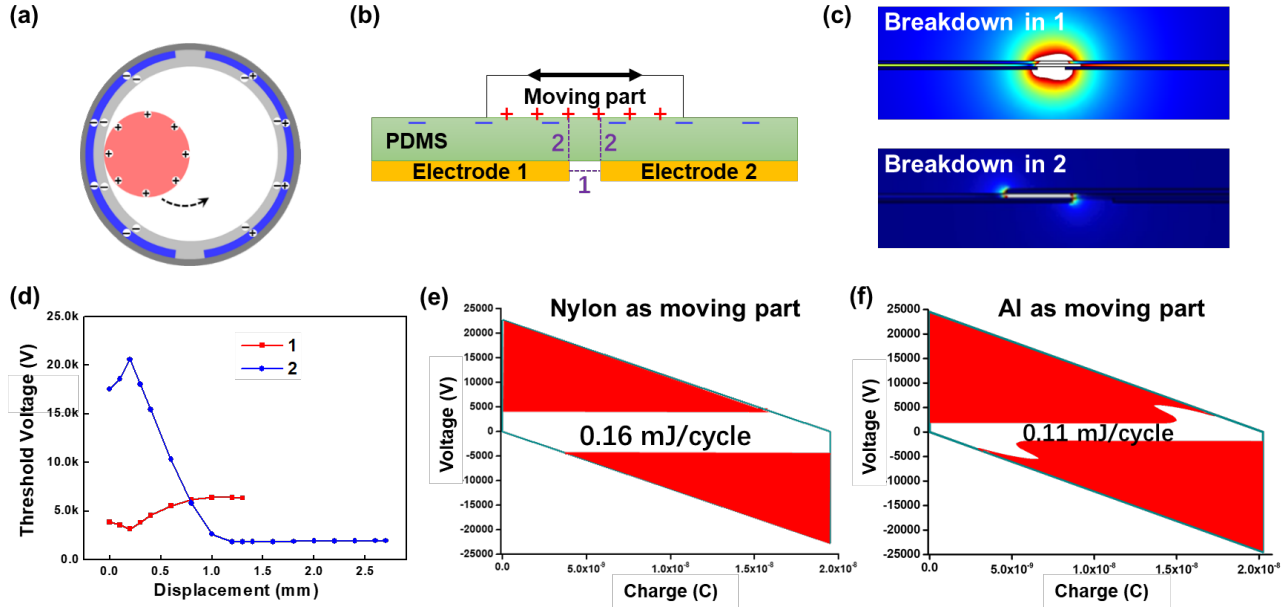

Figure 1: The modeling and simulation of water-wave TENG.

The original ball-shell structured TENG to harvest wave energy used in this project is schematically shown in **Fig. 1a**. Due to the triboelectrification, the electrons will be transferred from the electrodes to the ball. With the oscillations provided by the water waves, the inner moving ball can rotate from one electrode to the other one, which can electrostatically induce the potential difference between two electrodes, as the driven force of the current in the external circuits. To understand the breakdown effect in this water-wave TENG, the sliding-freestanding (SF) mode can be used to model this TENG. The schematic diagram of the SF-mode TENG is shown as **Fig. 1b**. There are two types of potential breakdown simulated, including horizontal air breakdown (type 1), and vertical dielectric breakdown (type 2). The model and simulations on the parasitic-capacitance effect have already been demonstrated and shown in the proposal previously.

The device breakdown criterion is set as below: if the minimum electric field along any line between electrodes or triboelectric surfaces is larger than the air-breakdown threshold electric field (3×10^6 V/m), then the breakdown happens, and there will be electron transfer between electrodes or triboelectric surfaces which can greatly impact the performance. The simulation of the electric field distribution is conducted in COMSOL Multiphysics software package, as shown in **Fig. 1c**. The simulated threshold voltages corresponding to different types of breakdown are plotted versus the displacement, as shown in **Fig. 1d**. And then we plotted the V-Q diagrams showing the breakdown regions in red, as shown in **Fig. 1e-f**. We notice that even though Al-PDMS friction can provide a little higher charge density, the TENG with insulating nylon as the moving layer can allow much more effective energy output (0.16 mJ/cycle) than that with conductive Al as the moving layer (0.11 mJ/cycle), due to the suppressed type-2 breakdown. Therefore, to avoid type-2 breakdown, we can choose insulating materials for the moving ball.

3.2 Experimental studies on the breakdown and parasitic-capacitance effects

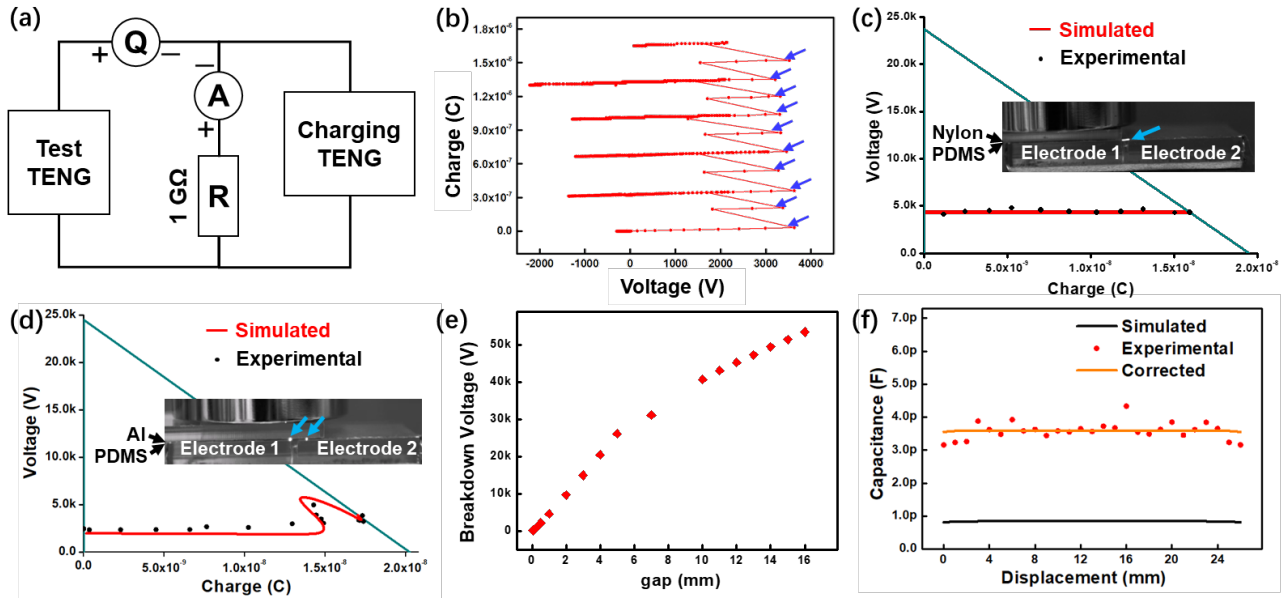

Figure 2: Experimental studies on the breakdown and parasitic-capacitance effects.

To directly observe the air-breakdown effect, we developed a measurement circuit to evaluate the breakdown effect, as shown in **Fig. 2a**. The hypothesis is, if there is breakdown happening, the measured V-Q plot will show clear turning points. The typically measured Q-V plots are shown in **Fig. 2b**, with the arrows indicating the breakdown points. As plotted in the V-Q diagram of the TENG, the experimental measured breakdown points are very consistent with the simulated results (**Fig. 2c-d**). The breakdown sparks are clearly observed through a high-speed camera, as indicated by arrows in the **insets of Fig. 2c-d**. We also experimentally demonstrated that the type-1 breakdown voltage can increase with the gap distance between electrodes (**Fig. 2e**), as a method to decrease the breakdown effect. This effect can be suppressed further within high-pressure inert environment.

We also revealed the parasitic-capacitance effect. Due to this effect, the measured capacitance values are much larger than the simulated results, as shown in **Fig. 2f**. After several repeated test, we can consider the average value of the difference between the simulated and the experimental capacitances as the parasitic capacitance. And then the corrected theoretical capacitance is calculated and plotted as the orange line, which is consistent with experimental results.

3.3 Optimized design of the water-wave TENG

In order to suppress the breakdown effect through the high pressure and inert gas environment, we modified the TENG structure design, as shown in **Fig. 3a inset**. To compare the output electric performances under different environment, the 1 atm air and 1.5 atm CO_2 were filled inside, respectively, and the results are shown in **Fig. 3a-b**. From these plots, we can conclude that the 1.5 atm CO_2 can greatly enhance the open-circuit voltage and short-circuit charge by both around 1.6 times, by suppressing the air-breakdown effect.

When the TENG is operated in water, the tested voltage and charge outputs are reduced to ~80 V and ~22 nC, respectively, as shown in **Fig. 3c-d**, due to the parasitic-capacitance effect from the water. To reduce that, we fabricated an additional packaging layer outside, as shown in **Fig. 3c inset**. With that, the voltage and charge outputs are recovered to be ~190 V and ~40 nC, respectively (**Fig. 3c-d**). The overall capacitance is reduced from ~0.28 nF to be ~0.21 nF. These results are well consistent with our theoretical simulations.

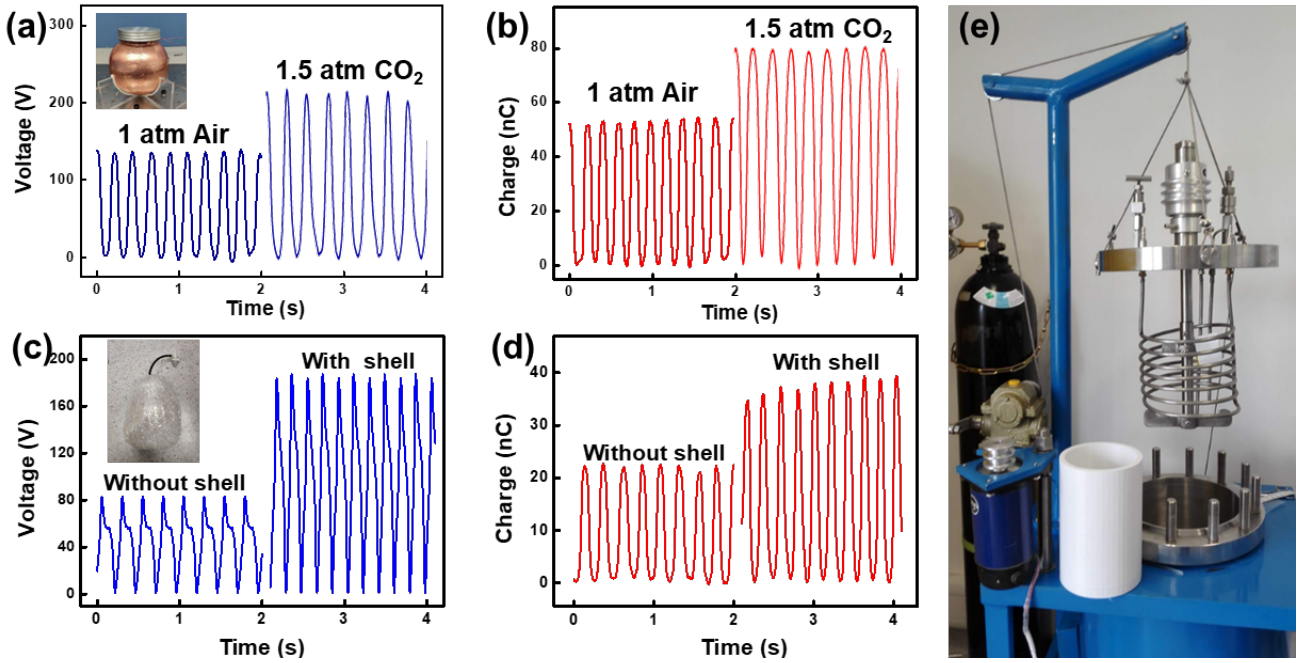

Figure 3: Optimized design of water-wave TENG and the high-pressure vessel

3.4 Development of the high-pressure vessel for quantitative analysis of the environmental factors

Even though we have demonstrated the optimized design, we still cannot evaluate and optimize the performance quantitatively, since it is impossible to control and maintain the internal environments very precisely. To address this issue and to test the device performance under even higher pressures, we have modified a steel-made chemical reactor (**Fig. 3e**) to provide the desired environment for the output performance evaluation of TENG. This reactor can withstand high pressure up to 15 MPa (148 atm). This reactor can provide quantitative controls on environmental factors, including pressure, gas concentration, temperature, *etc*. The stirring blades can provide the mechanical motions to mimic the water waves with various frequency and magnitude. When TENG is placed inside the vessel and floating on the water surface, the electrical measurement can be conducted under precisely-controlled environmental parameters. More results will be produced from this system in the future.

4. PUBLICATION AND AWARDS

J[1] G. Xu, X. Li, X. Xia, J. Fu, W. Ding, **Y. Zi**, "On the force and energy conversion in triboelectric nanogenerators," *Nano Energy*, Elsevier, Netherlands, 59, 154-161 (2019).

J[2] H. Wang, Q. Zhu, Z. Ding, Z. Li, H. Zheng, J. Fu, C. Diao, X. Zhang, J. Tian, **Y. Zi**, "A fully-packaged ship-shaped hybrid nanogenerator for blue energy harvesting toward seawater self-desalination and self-powered positioning," *Nano Energy*, Elsevier, Netherlands, 57, 616-624 (2019).

J[3] F. Chen, Y. Wu, Z. Ding, X. Xia, S. Li, H. Zheng, C. Diao, G. Yue, **Y. Zi**, "A Novel Triboelectric Nanogenerator Based on Electrospun Polyvinylidene Fluoride Nanofibers for Effective Acoustic Energy Harvesting and Self-powered Multifunctional Sensing," *Nano Energy*, Elsevier, Netherlands, 56, 241-251 (2019).

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*J[5] Z. Wen, J. Fu, L. Han, Y. Liu, M. Peng, L. Zheng, Y. Zhu, X. Sun, **Y. Zi**, "Toward Self-powered Photodetection Enabled by Triboelectric Nanogenerators," Journal of Materials Chemistry C, The Royal Society of Chemistry, United Kingdoms, 6, 11893-11902 (2018).*

COMPLETED

TUNABLE SPINDLE USING SELF-EXCITED VIBRATION FOR HIGH EFFICIENCY RENEWABLE ELECTRIC GENERATORS

Principal Investigator: Professor Wei-Hsin LIAO
Department of Mechanical & Automation Engineering, CUHK

Co-Investigator: Professor Ping GUO [(1)]

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Project Start Date: 1 July 2017
Completion Date: 14 August 2019

INNOVATION AND PRACTICAL SIGNIFICANCE:

This project proposes a novel spindle design for renewable electric generators, which utilizes high frequency vibration for improved tribological performance, higher energy efficiency, and reduced wear. The proposed design is supported by three major innovations: **(1)** vibration-induced friction reduction; **(2)** self-excited vibration without any extra power supply; and **(3)** a tunable spindle structure for a wide operation range. This project, if successful, will significantly improve the performance of traditional renewable electric generators in terms of efficiency and lifetime, which have play an ever increasing role in the era of clean energy.

ABSTRACT

Considering the world population growth, diminishing of fossil fuel sources, and environmental pollution, the use of renewable resources, such as hydroelectric, nuclear, and wind energy, has been emerging as an important form of clean energy. The core functional part in these renewal energy technologies is an electric generator. One critical issue determining the efficiency and reliability of renewable electric generators lies in the interaction between the spindle shaft and bearing surfaces. The friction coefficient largely influences the power generation efficiency while the contact condition determines the wear rate of the shaft and bearings. This project proposes a novel spindle design for renewable electric generators, which utilizes high frequency vibration for improved tribological performance, higher energy efficiency, and reduced wear. The proposed design is supported by three major innovations: (1) vibration-induced friction reduction; (2) self-excited vibration without any extra power supply; and (3) a tunable spindle structure for a wide operation range. The proposed design has a high potential for commercialization due to its much improved performance without major increase in cost and design complexity. This project, if successful, will not only help the development of fundamental research but also the application of renewable electric generators.

1. OBJECTIVES AND SIGNIFICANCE

This project proposes a novel spindle design for renewable electric generators, which utilizes high frequency vibration for improved tribological performance, higher energy efficiency, and reduced wear. The proposed design is supported by three major innovations: (1) vibration-induced friction reduction; (2) self-excited vibration without any extra power supply; and (3) a tunable spindle structure for a wide operation range. This

project, if successful, will significantly improve the performance of traditional renewable electric generators in terms of efficiency and lifetime, which have play an ever increasing role in the era of clean energy.

2. RESEARCH METHODOLOGY

This research project will be carried out to accomplish a prolonged bearing lifetime for the rotating-spindle-type electric generators together with a higher energy efficiency. There are three main research tasks in this project:

(1) Propose a low friction bearing technology by the principle of vibration-induced friction reduction to prolong the lifetime of high-load bearings and increase the power efficiency in rotating-spindle-type electric generators.

(2) Establish a self-tunable vibration generating device without extra electric power supply or piezoelectric elements, which reduces the extra cost for vibration system and simplifies the overall structure.

(3) Realize a self-excited vibration spindle system accommodated with position-adjustable-bearings, which is capable of changing the resonant frequency of the spindle. Therefore, an optimized vibration-induced friction reduction effect will be accessible when the self-excited vibration frequency is in accordance with the resonant one.

3. RESULTS ACHIEVED

3.1. Research Progress

3.1.1. Non-contact journal bearing

We have developed a non-contact journal bearing with bi-directional driving capability utilizing the coupled resonant mode. It combines the functions of an axis positioner, non-contact journal bearing, and rotary motor. The shaft levitation is achieved by creating a stable air film using near-field acoustic force; while the non-contact rotation is realized by controlling the pressure distribution within the air film using coupled resonant mode. The mechanism of non-contact rotation can be explained by the schematics shown in Figure 1. Unlike previous designs utilizing a traveling wave and viscous shear force, the rotational driving force is mainly contributed by the tangential component of the levitation pressure. During the compression stage of the air film, due to the slope angle of the bearing upper surface, the net reaction force from the air produces a circumferential force acting in the counter clockwise direction of the shaft. During the release stage, both the bearing surface slope angle and the pressure force change the direction, so the net reaction force still produces a counter clockwise torque on the shaft. For both the compression and expansion stages, the reaction force applied on the shaft has a circumferential component in the same direction. The experimental results of the levitation and rotational driving tests are summarized in Figure 2.

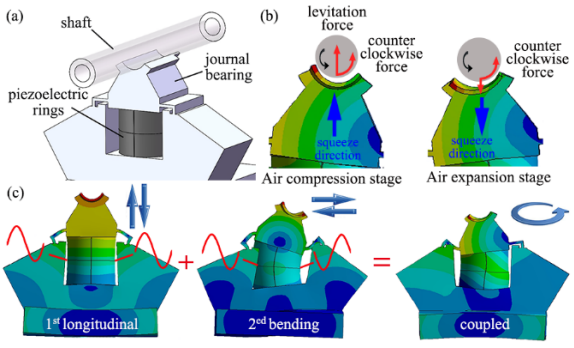

Figure 1. (a) Design of a single driving unit; (b) operation principle for shaft levitation and rotation; and (c) coupled mode shapes.

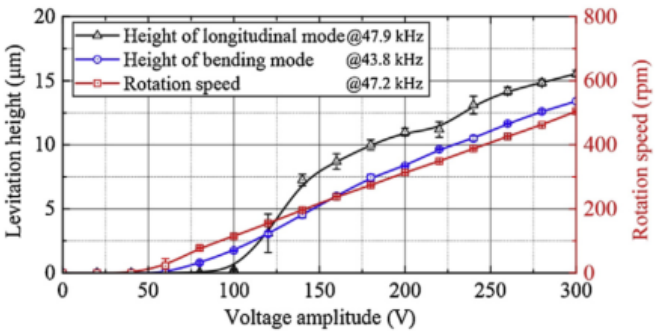

Figure 2 Performance evaluation of levitation height and rotation speed

The non-contact shaft rotation can be achieved and controlled by exciting the structure at a frequency

between the two modes and adjusting the input phase angle or input voltage amplitude. The bearing was excited at 47.2 kHz with a voltage amplitude of 300 V, while the phase angle was adjusted from -180° to +180°. The relationship between the rotation direction as well as speed and the input phase angle is plotted in Figure 3. The bearing demonstrated identical performance when rotated in the clockwise and counter clockwise directions. The rotation speed reached a peak value of ±555 rpm at a phase angle of 70°. The bearing could be switched to a pure levitation state by setting the phase angle to 0° or 180°.

Based on the design principle proposed in this project, an advanced functional prototype with six driving units was fabricated for two-dimensional radial position control. The 3D model and functional prototype are shown in Figure 4. The main body of a U-shaped bearing frame was fabricated from a single aluminum alloy workpiece using electrical discharge machining (EDM) to ensure the coaxiality between the two sets of driving units. On each side, three identical driving units are placed 120° apart. Each driving unit functions similarly as the single unit described in the previous sections. The overall operating frequency of this design would be higher than that in a single unit due to the increased stiffness from the unibody design.

In additional to the levitation and rotation control, the radial position control capability is demonstrated. The driving units were grouped by their angular position and controlled by the signals #1 – #3, as shown in Figure 4. In the vertical direction, the shaft position could be controlled in a range of 18.3 μm, when the signals #1 and #2 were simultaneously varied from 100 V to 350 V. The minimal stable increment could reach 200 nm when the voltage increment was 5 V, as shown in Fig. 4(a). In the lateral direction, the radial position could be controlled in a range of 2.1 μm, when we adjusted the amplitudes of signals #1 and #2 in the opposite direction. The minimal stable increment could also reach 200 nm when the voltage increment was 10 V, as shown in Figure 5(b). Finally, the radial runout was measured at a rotation speed of 512 rpm, when the driving frequency was 64.9 kHz with a 75° phase shift angle. The total indicator runout was within 6 μm as indicated in Figure 5(c), which is a combination from the shaft form inaccuracy and spindle runout.

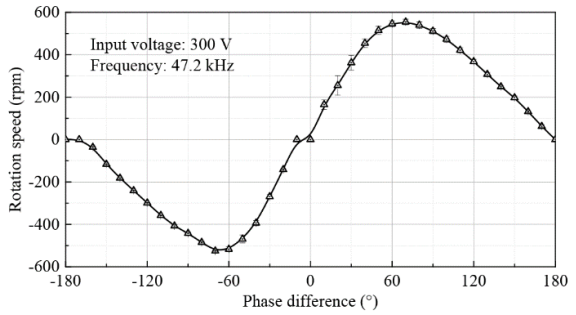

Figure 3. The relationship between rotation speed and phase angle.

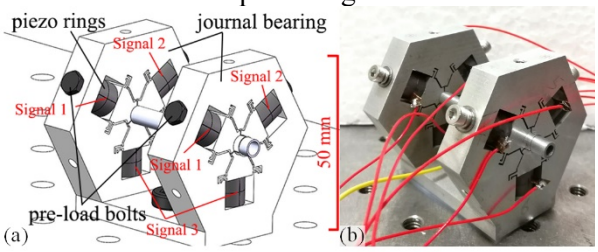

Figure 4. Design of the active non-contact journal bearing with six driving units: (a) 3D model and (b) functional prototype.

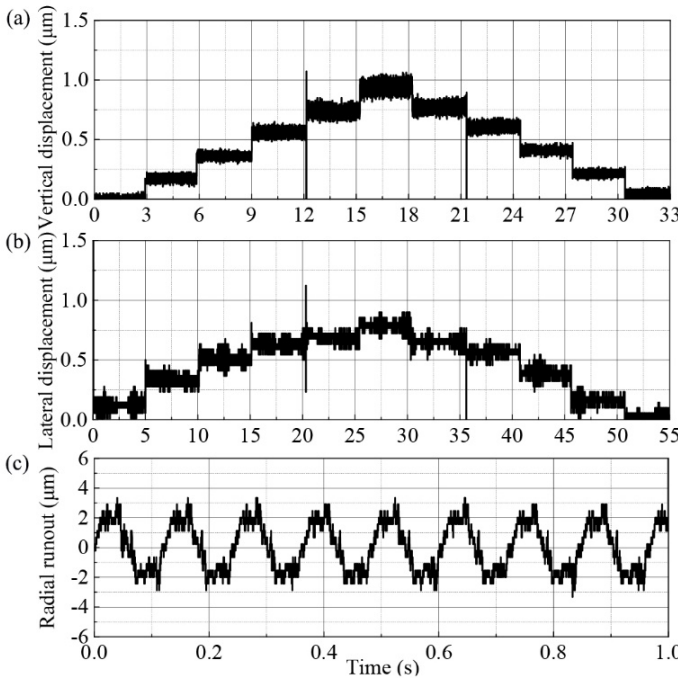

Figure 5. Active axis position control in the (a) vertical and (b) lateral directions; and (c) shaft runout during rotation.

3.1.2. Wireless self-running and self-levitation robot

We have developed a wireless self-running and self-levitation robot based on near-field acoustic levitation to eliminate the effect of wires and make the system compact. Compared with conventional ultrasonic devices, levitation and actuation systems are decoupled in the proposed design. In the levitation part, the robot is

equipped with four round vibrators in the same type, each of which consists of a piezoelectric disk and an aluminum plate, as shown in Figure 6. These vibrators are arranged symmetrically about the center point in order to counterbalance any horizontal forces induced by them, creating a stable and pure levitation environment. In the propulsion system, two identical blade motors are responsible for the generation of thrust forces, even steering the robot by controlling their output powers separately. It is worthy of mentioning that we adopted wireless control on both levitation and actuation systems using Bluetooth communication, through which excitation frequencies applied to piezoelectric elements and output powers of motors can be adjusted. For the circuit part, LLCC resonant loop is the core of whole system for reducing input power by exchanging remaining energy in piezo actuator and main resonant coil. To yield enough high voltages on piezo, a two-stage boost circuit is used to convert a 7.4 Volts input of two lithium-ion batteries in series to an output of 60 Volts. About driving signal, PWM reduces low order voltage harmonics. Since lower low order harmonics, LLCC will be much easier to design and adjust. This driving signal is precisely generated using direct digital synthesis (DDS) chips, comparator and inverter. Without FPGA, a simple microcontroller is enough to set driving and modulation frequencies, to control phase and to deal with other parts of the circuit. This novel design has a promising future in the fields of transfer robots in logistics factories and warehouses with its high load capacity and high trajectory controbilities.

We have developed models which governs structural dynamics of the robot and fluid flow as illustrated in Figure 7. Simulation on the flow field of air in the gap between the plate and substrate are also performed utilizing finite-element analysis (FEA) by COMSOL Multiphysics 5.4. Navier-Stoke equations are used to describe the airflow in the domain. In particular, laminar flow assumption is adopted for computation simplification, since the simulation serves to explain the root cause of robot levitation qualitatively. A series of experiments on the performance of the robot have been conducted, including measurements on travel velocity, levitation height, working efficiency and thrust force. In the experiment as shown in Figure 8, we swept frequencies ranging from 18 kHz to 35 kHz on a piezo element with an amplitude of 120 Vpp. Loads applied to the test actuator was 15 g, one fourth of the robot weight. By comparing phase and magnitude information between detected signals and input signals, frequencies could be determined. Subsequently, the electrical signal of the obtained frequency was imposed onto another piezo element checking the reliability of the results, since the four disks were placed symmetrically. From simulation results, it is found that the fourth mode shape of circular plates brings the best performance of levitation among obtainable modes. Actuators with the fourth mode shape yields high vibration amplitudes and the frequency of the mode is 23.213 kHz, electrical circuit friendly. The experimental result is 24.8 kHz, which means the simulation result has only 6.4 percent error. Figure 9 showed the results of forced vibration tests. Experiment results also showed this proposed robot possesses higher energy efficiency than conventional levitation stages.

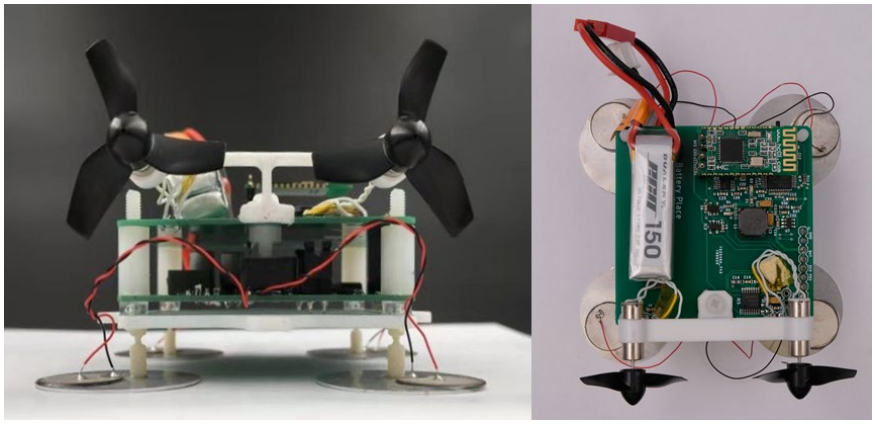

Figure 6. Front and top views of the levitation robot

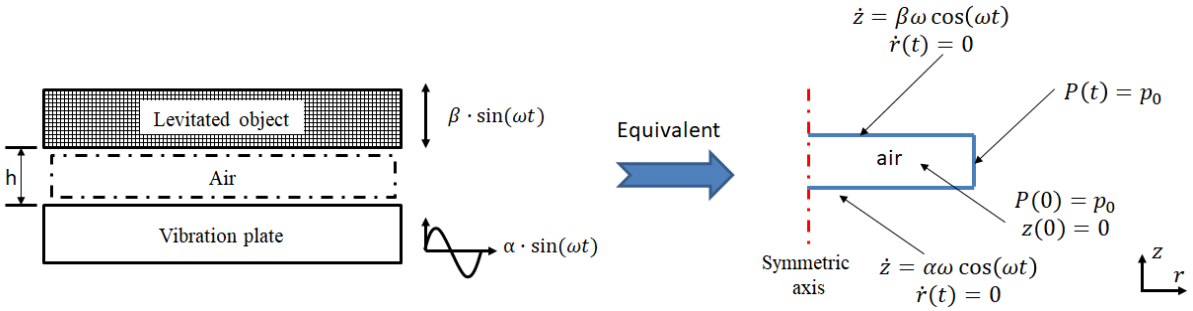

Figure 7. Schematics of forced vibration system (left) and equivalent model of the system (right)

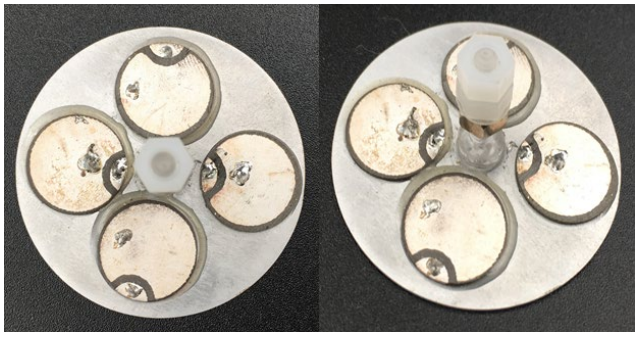

Figure 8. Schematics of actuators for finding resonant frequencies and vibration shapes

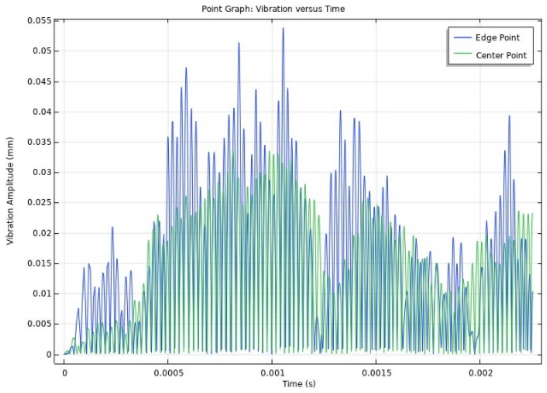

Figure 9. Vibrations of edge point and center point for 50 periods. The excitation is set at 22.203 kHz.

3.2. Commercialization Efforts

3.2.1. Press Conference

We have made a press conference at CUHK on Oct 9, 2017 about our research outputs, which was reported by a number of local media, including Sing Tao Daily, Ming Pao, Oriental Daily News, Hong Kong Economic Journal, Apple Daily, Wen Wei Po, Ta Kung Pao, Metro Daily, Headling Daily, Sky Post, Hong Kong Commercial Daily, Sing Pao, South China Morning Post, etc. One of the press released photo is attached for reference (shown in Figure 10).

3.2.2. Exhibition at InnoCarnival 2017

We have demoed our work, levitating actuator using near-field acoustic, at the Inno Carnival at the science park during Oct 21 – 29. It attracted some attention from different investors. The highlight includes the presentation of our project to Secretary for Innovation and Technology of Hong Kong, as shown in the attached figure (Figure 11).

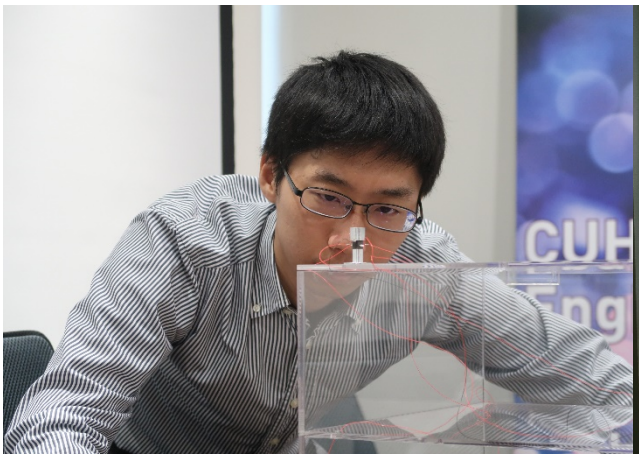

Figure 10. Press conference photo

Figure 11. Presentation at InnoCarnival 2017

3.2.3. Hasbro Presentation

We have presented our research results at the Tech Summit of Hasbro, Hong Kong on October 18. Hasbro is an American-based multinational toy and board game company (which makes the board game, Monopoly). The company showed some interest in our technology.

3.2.4. Academic Presentation

We have also presented our work in various academic settings and invited presentations, including Northwestern University (Jan 29, 2018, USA), Technical University of Denmark (May 22, 2018, Denmark), and KTH Royal Institute of Technology in Stockholm (May 25, 2018, Sweden).

4. PUBLICATION AND AWARDS

J[1] J. Wang, P. Feng, J. Zhang, and P. Guo, "Experimental study on vibration stability in rotary ultrasonic machining of ceramic matrix composites: Cutting force variation at hole entrance," Ceramics International, 2018.

J[2] P. Guo and H. Gao, "An active non-contact journal bearing with bi-directional driving capability utilizing coupled resonant mode," CIRP Annals Manufacturing Technology, 2018.

J[3] J. Wang, H. Du, S. Gao, Y. Yang, Z. Zhu, and P. Guo. "An ultrafast 2-D non-resonant cutting tool for texturing micro-structured surfaces," Journal of Manufacturing Processes, 2019.

J[4] J. Wang, Y. Yang, R. Yang, P. Feng, and P. Guo. "On the validity of compliance-based matrix method in output compliance modeling of flexure-hinge mechanism," Precision Engineering, 2019

C[5] S. Gao and P. Guo, "Modeling and tool trajectory monitoring of an ultrasonic elliptical vibration tool," International Symposium on Flexible Automation, Kanazawa, Japan, 15-19 July, 2018.

C[6] R. Yang, J. Huang and P. Guo, "Frequency dependence of levitation force in near-field acoustic levitation," International Symposium on Flexible Automation, Kanazawa, Japan, 15-19 July, 2018.

C[7] J. Wang, Y. Yang, and P. Guo, "Effects of vibration trajectory on ductile-to-brittle transition in vibration cutting of single crystal silicon using a non-resonant tool," CIRP Conference on Surface Integrity, Tianjin, 11-13 July, China.

J[8] J. Wang, W. H. Liao, and P. Guo, "Modulated Ultrasonic Elliptical Vibration Cutting for Ductile-Regime Texturing of Brittle Materials with 2-D Combined Resonant and Non-Resonant Vibrations, *International Journal of Mechanical Sciences*, Vol. 170, 105347, 2020.

J[9] Q. Gao, W. H. Liao, and L. Wang, "An Analytical Model of Cylindrical Double-Arrowed Honeycomb with Negative Poisson's Ratio," *International Journal of Mechanical Sciences*, Vol. 173, 105400, 2020.

J[10] Q. Gao, W. H. Liao, and L. Wang, "On the Low-Velocity Impact Responses of Auxetic Double Arrowed Honeycomb," *Aerospace Science and Technology*, Vol. 98, 105698, 2020.

J[11] J. Wang, Y. Yang, Z. Zhu, Y. Wang, W. H. Liao, and P. Guo, "On Ductile-Regime Elliptical Vibration Cutting of Silicon with Identifying the Lower Bound of Practicable Nominal Cutting Velocity," *Journal of Materials Processing Technology*, Vol. 283, 116720, 2020.

Biomedical Engineering Track

Research Reports In Biomedical Engineering

Newly Funded Projects (2020-2022)	* Development of deep-learning assisted ultrahigh-resolution endoscopic OCT for visualization and quantification of volumetric small airway microstructures in vivo
	* Development of a cell-derived extracellular matrix-based biomaterial for the treatment of osteoarthritis
	* A dexterous robot for endoscopic submucosal dissection in the colon
Continuing Projects (2019-2021)	* Development of a Folded bilayer Scaffold for Intestinal Tissue Engineering
	* Optogenetic Regulation of Hormone Production for Glucose Homeostasis Maintenance
(2018-2020)	* Development of Highly Sensitive Quantitative Phase Microscopy for Label-free Imaging of Neuronal Network Activities
Completed Projects (2017-2019)	* Development of a Novel Robotic Manipulator for Confined Space Surgery
	* Development of an Inertial Microfluidics Based Approach for the Isolation of Mitochondria from Biological Samples

The following reports are enclosed in "Research Highlights" printed in June 2019

Completed Projects (2016-2018)	* An MRI-guided Robotic System for Breast Biopsy * Intention-driven Shoulder Rehabilitation for Targeted Meuro-muscular Training using an Exo-musculoskeletal Robot * Engineering Antimicrobial Surfaces Based on Micro-topography Using a Novel Ultrasonic Machining Method

The following reports are enclosed in "Research Highlights" printed in July 2018

Completed Projects (2015-2017)	* Development of a Novel flexible Surgical Robot with Haptic Sensation * Development of Injectable Supramolecular Hydrogels for Regenerative Medicine * Developing Optomechanical Devices based on Layered Nanomaterials for Single-Biomolecule Mass Spectrometry

The following reports are enclosed in "Research Highlights" printed in August 2017

Completed Projects (2014-2016)	* Development of High-speed Laser Scanning Microscope for In Vivo Deep Brain Imaging * Mechanism for the Transcytosis of Targeted Nanoparticles Across the Blood-brain barrier
(2013-2015)	* Development of the Next Generation Neurosurgical Assistant System Based on Functional Brain Mapping * Biomimetic Scaffold for Stem Cell Based Cartilage Regeneration and Drug Delivery

The following reports are enclosed in "Research Highlights" printed in June 2015

Completed Project (2012)	* Dielectrophoresis Nano-separator for Precision Manufacturing of Polymeric Nanoparticles for Tumor-Targeted Drug Delivery

The following reports are enclosed in "Research Highlights" printed in June 2014

Completed Project (2011)	* Viewing Biomolecules at the Right Site by Plasmonic Tweezers and Surface Enhanced Raman Scattering

The following reports are enclosed in "Research Highlights" printed in 2013

Completed Projects (2010)	* An inexpensive functional finger prosthesis with rebounded type progressive hinge lock * Diffusion Tensor MRI Predictors of Cognitive Impairment in Confluent White Matter Lesion * Lanthanide-impregnated Molecularly Imprinted Polymer Microspheres as Antibody Mimics on an Optofluidic Platform for the detection of Disease Biomarkers

Completed Projects	(2009)	* Terahertz Probe for in Vivo Imaging * Signal Processing Strategies on Cochlear Implant Devices for Effective Speech Perception of Tonal Languages * Development of A Robotic Endoscope Holder for Nasal Surgery

The following reports are enclosed in "General Report and Research Highlights 2009-2011" printed in October 2011.

Completed Project	(2008)	* Development of Highly Sensitive and Large Throughput Surface Enhanced Raman Scattering (SERS) Substrates for Molecular Diagnosis * Research on Language and Brain Waves * Development of an Efficient Locomotion Mechanism for Wireless Active Capsule Endoscope
	(2007)	* Bio-electromagnetic Modeling and Experiment Setup for Medical Electronics RF Safety Assessment * Medical Applications of Terahertz Imaging * Hybrid Assistive Knee Braces with Smart Actuators
	(2006)	* RF Radiation Effect and Efficiency of Wireless Medical Devices on Human Body * Photonic Biosensor Micro-arrays for Screening of Common Cancers

The following reports are enclosed in "Research Highlights 2005-2007" printed in January 2008.

Completed Projects	(2005)	* Cochlear Implants * Virtual Anatomy and Dexterous Simulators for Minimal Access Cardiothoracic and Neuro-endoscopic Surgeries * Systematic Synthesis of Nano-informatics Chips by Nano-Robotics Manipulation

(Funded Year)

DEVELOPMENT OF DEEP-LEARNING ASSISTED ULTRAHIGH-RESOLUTION ENDOSCOPIC OCT FOR VISUALIZATION AND QUANTIFICATION OF VOLUMETRIC SMALL AIRWAY MICROSTRUCTURES IN VIVO

Principal Investigator: Professor Wu YUAN
Department of Biomedical Engineering, CUHK

Project Start Date: 1 August 2020

ABSTRACT

In vivo visualization and quantification of the microstructures of small airways (of a lumen diameter <2 mm) allows a better understanding and management of asthma and chronic obstructive pulmonary disease (COPD). At present, the resolution and contrast of the clinically available imaging technologies (such as micro-CT and MRI) and conventional optical coherence tomography (OCT) operating at 1300 nm are insufficient to resolve the fine microstructures of small airways in vivo. In addition, the high-speed OCT generates a large amount of volumetric imaging data (up to tens of GBs), making manual image reading extremely laborious if not impossible.

In this project, we aim to develop a deep-learning aided high-speed, ultrahigh-resolution endoscopic OCT technology for automatic volumetric measurements of small airway pathology in vivo. We propose to: (1) develop a portable endoscopic OCT system at 800 nm with a resolving power of ≤2 μm and improved contrast for accurately delineating small airway microstructures, (2) develop a deep-learning neural network algorithm to enable the automatic interpretation and quantification of critical tissue compartments of small airways in three dimensions (3D), and (3) incorporate the deep learning algorithm into the portable OCT system to enable the operational feasibility for imaging and quantification of small airways in patients.

INNOVATION AND PRACTICAL SIGNIFICANCE:

There are several novel aspects to this project:

First, the new endoscopic OCT system, including a novel high-speed 800-nm OCT engine (with an A-line speed up to 250 kHz), a fast rotary joint (for imaging speed more than 20 frames/sec), and a miniaturized and achromatic imaging endoscope (of a diameter less than 2 mm), is able to offer a superior imaging resolution (versus 1300-nm OCT) for accurate delineation of small airway microstructures, such as the epithelium, lamina propria, airway smooth muscle, glands, and blood vessels, in vivo and in video rate.

Second, with a powerful deep-learning neural network, we will be able to cope with the increasing volume of OCT images and the shortage of available human expertise, and achieve an automatic segment, quantify, and visualize the important tissue compartments in small airways in 3D. Such a

tool would potentially provide a critical step to perform objective pathology assessment in vivo and in real time.

Third, the portable configuration of our endoscopic OCT system will help the future clinical translation. The small form factor of the imaging endoscope enables its direct deployment through the working channel of bronchoscope in clinic for minimal-invasively imaging the small airways in patients.

In summary, the capability to directly visualize and quantify airway smooth muscle and other critical tissue compartments in small airways in vivo, which are the critical pathology sites related to asthma and COPD, offers an unique opportunity for longitudinally studying the pathogenesis, determining the severity, phenotyping, guiding and monitoring the response to treatment in related pulmonary diseases.

PROJECT OBJECTIVES AND LONG-TERM IMPACT:

Aim 1. Develop a portable, high-speed OCT engine and a fast rotary joint operating at 800 nm to enable the ultrahigh resolution and potential video-rate imaging of the small airways of patients in clinic.

Expected outcome/impact: The axial resolution is limited to ~10 μm with conventional OCT operating at 1300 nm, which is suboptimal for accurately resolving fine tissue structures or subtle pathologic changes associated with early diseases. By moving the central wavelength from 1300 to 800 nm, the axial resolution can be greatly improved from 10 μm down to several microns. The portable OCT system will operate at 800 nm with a broad spectral bandwidth, offering cellular resolution (≤2 μm) to delineate fine microstructures in small airway walls. The new OCT engine will acquire the image with an A-line speed up to 250 kHz. The high-speed rotary joint (not commercially available at 800 nm) will perform circumferential scan of the endoscope at speed more than 20 frames/sec to enable a real-time volumetric imaging of small airways.

Aim 2. Design and fabricate achromatic endoscopes of compact size (<2 mm) to work with bronchoscope for accurately assessing fine microstructures in the peripheral small airways in vivo.

Expected outcome/impact: To overcome the severe chromatic aberration faced by the conventional GRIN-lens based micro-optics in OCT endoscopes when using a broad spectrum at 800 nm, the new endoscope will adopt a novel optics design, offering the achromatic performance and thus the ultrahigh resolution. The OCT endoscope will have the ability to identify different components of the airway wall microstructure. It is the changes in these microstructures that lead to changes in airway function in asthma and COPD. In addition, our OCT endoscope will afford high-resolution 3D in vivo “optical biopsy” of internal luminal organs, such as blood vessels, enabling disease diagnosis and screening where traditional biopsy suffers from sampling error or risk of complications.

Aim 3. Develop a deep-learning neural network algorithm for automatic segmentation of small airway microstructures with the accuracy comparable to human expert and incorporate the deep-learning algorithm into the portable OCT system for potential clinical use.

Expected outcome/impact: Conventionally, OCT images could not be directly interpreted by clinicians without special training. More importantly, the high-speed OCT generates a large amount of volumetric imaging data (up to tens of GBs). Therefore, an automatic OCT image assessment tool with an accuracy comparable with the expert reviewer is highly desirable to cope with the increasing volume of diagnostic imaging and the short of available human expertise to interpret it. The deep-learning assisted real-time tissue assessment on 3D OCT images in vivo will further enhance the clinical viability of our endoscopic OCT imaging technique to perform objective pathology assessment in vivo and in real time.

DEVELOPMENT OF A CELL-DERIVED EXTRACELLULAR MATRIX-BASED BIOMATERIAL FOR THE TREATMENT OF OSTEOARTHRITIS

Principal Investigator: Professor BLOCKI, Anna Maria
Institute for Tissue Engineering and Regenerative Medicine, Department of Biomedical Engineering, CUHK

Project Start Date: 1 September 2020

ABSTRACT

Osteoarthritis (OA) is the most common degenerative joint disease and a major cause of pain and disability in adults. Chronic inflammation is believed to be a major factor in the progression of OA. Mesenchymal stem cells (MSCs) exhibit great potential to treat OA, due to their anti-inflammatory properties mediated via secreted factors. Nonetheless, MSCs demonstrated limited therapeutic efficacy due to their low survival rate in the hostile chronically inflamed environment. Direct application of MSC-secreted factors met also with limited efficacy, as these factors exhibit a short half-life.
We propose to overcome these limitations by closely mimicking the natural state, in which cell-derived signalling factors are protected in tissue, namely in the form of the extracellular matrix (ECM).
We have established an approach to engineer MSC-derived ECM-based composite biomaterials with improved anti-inflammatory properties. To further develop this strategy for clinical application we propose to (1) investigate the long-term stability and bioactivity of the engineered biomaterials; (2) evaluate the therapeutic efficacy of the engineered biomaterials in a pre-clinical osteochondral defect model.
The successful completion of this project will provide an engineering approach to overcome the limitations of MSC-based therapy and potentially an effective treatment for the chronically inflamed environment in OA.

INNOVATION AND PRACTICAL SIGNIFICANCE:

The major innovation of the current work lies in the design of a biomaterial based on cell-derived ECM, which potentially enables the delivery and long-term stabilization of cell-derived therapeutic signaling factors. We have already filed a provisional patent application in May 2019 (Anna Blocki and Marisa Assuncao, Chinese University of Hong Kong (2019) "Process and material for tissue healing" US provisional patent application: 62/848,971), protecting this material design.
By utilizing this biomaterial, we are able to address major limitations of cell-based therapies, such as limited engraftment and survival of transplanted cells, limited therapeutic efficacy of conditioned media, immunological concerns, when allogeneic cell sources are utilized (ECM is highly conserved and thus not evoke an immune response), etc. At the same time, the engineered biomaterial exhibits the necessary complex bioactivity to guide complex tissue healing processes, in

contrast to selected biologics or simple scaffolds

The unique techniques utilized, enable the synthesis of larger amounts of biomaterial, thereby ensuring a stable/reproducible bioactivity and are necessary for future scale-up production.
The bioactive material can be stored and thus utilized off-the-shelf. It can be processed and incorporated in all types of materials including tissue scaffolds, implants, wound dressings and (injectable) hydrogels. Hence, just by itself or incorporated into other materials, it can be applied to tissue areas with chronically inflamed and dysregulated microenvironments, thereby modulating and turning the diseased environment into a pre-healing one. This will advance the healing and regeneration process in non-healing and non-regenerative tissues such as osteoarthritis and beyond.

PROJECT OBJECTIVES AND LONG-TERM IMPORT:

1. Purpose: Osteoarthritis (OA) is the most common degenerative joint disease. It affects cartilage tissue and the underlying bone, is a major cause of pain and disability in adults and does not have an effective treatment. Chronic inflammation, which occurs due to the limited healing potential of cartilage is believed to be a major factor in the progression of OA[1].

2. Key problem: Mesenchymal stem cell (MSC)-based therapies exhibit great potential to treat OA[1], due to their anti-inflammatory properties mediated via their secreted signaling factors[2]. Nonetheless, MSCs demonstrated limited therapeutic efficacy, due to their low survival rate, when facing the hostile environment in a chronically inflamed OA joint[1]. Direct application of MSC-secreted factors met also with limited therapeutic efficacy, as soluble signaling factors have a too short half-life[3].

3. Proposed solution: We propose a bio-inspired engineering approach by closely mimicking the natural state, in which cell-derived signalling factors are protected in tissue, namely in the form of the extracellular matrix (ECM)[4].
Thus, we have established an approach to engineer MSC-derived ECM-based composite biomaterials with improved anti-inflammatory properties *in vitro* in sufficient amounts to ensure a stable bioactivity (Fig.1).

4. Aim 1: Investigation of long-term stability and bioactivity of engineered MSC-derived ECM-based biomaterials even under harsh conditions.

5. Aim 2: *In vivo* evaluation of therapeutic efficacy of engineered MSC-derived ECM-based biomaterials in a pre-clinical osteochondral defect model.

6. Envisioned outcome: The engineered MSC-derived ECM-based biomaterial will exhibit strong and long-lived anti-inflammatory properties, which can even sustain harsh conditions, as the ECM format will protect the embedded bioactive factors from degradation. The long-lived bioactivity will ensure a lasting effect, thereby attenuating chronic inflammation and promoting cartilage repair in an animal osteochondral defect model.

7. Relevance: The successful completion of this project will provide an engineering approach to overcome the limitations of MSC- based therapy and potentially provide an effective treatment of the chronically inflamed environment in OA.

A DEXTEROUS ROBOT FOR ENDOSCOPIC SUBMUCOSAL DISSECTION IN THE COLON

Principal Investigator: Professor CHENG, Shing Shin
Department of Mechanical & Automation Engineering
CUHK

Project Start Date: 1 September 2020

ABSTRACT

Endoscopic submucosal dissection (ESD) is an effective minimally invasive treatment for early colorectal cancer. However, it is challenging to perform ESD with existing instruments due to the lack of distal dexterity and stable visualization. While dual-channel flexible endoscopic systems have been developed for general transluminal surgery in the recent decade, their performance has been limited by the lack of operation stability, miniaturization issue, system complexity, and lack of haptic feedback. Therefore, the proposed research aims at developing a dexterous endoscopic robot for single-channel colonoscope to perform ESD. The 2-segment, 5-DoF robot, based on the notched tube design, will be miniaturized to 3mm diameter to fit the instrument channel of colonoscope. The design will be optimized to ensure motion decoupling between its segments, allowing stable operation. An accurate mechanics model that takes into account stiffness variation between segments will be developed. The hysteresis, mainly originated from the flexible body, will be characterized, modeled, and taken into account in the control. A force controller will also be developed using force feedback obtained from the integrated Fiber Bragg Grating sensor. The robot will be evaluated for its performance through benchtop performance and tested its feasibility in a phantom colon.

INNOVATION AND PRACTICAL SIGNIFICANCE:

The proposed research focuses on the development of a dexterous endoscopic robot for performing endoscopic submucosal dissection (ESD) in the colon. Currently, ESD is performed manually using an instrument such as an ITknife 2 that passes through the 3.2mm-diameter instrument channel of a colonoscope. The limited degree-of-freedom (DoF) of only translation of the instrument requires the distal part of the colonoscope to be maneuvered together with the instrument, leading to unstable visualization that hinders effective execution of ESD. The procedure also requires coordination between an endoscopist and an assistant nurse who are responsible for manipulating the colonoscope and the instrument, respectively, which is a challenging task. ***The proposed research addresses these challenges by developing a two-segment dexterous endoscopic robot with five DoFs, namely distal segment bending in pitch and yaw, proximal segment bending in pitch, robot translation, and self-axis robot rotation. The ability to steer the ESD instrument dexterously allows the colonoscope to act as a stable visualization platform. The teleoperation control of the multi-DoF robot also allows the entire ESD procedure to be handled by one endoscopist, potentially leading to higher performance and productivity.***

While dual-arm flexible endoscopic robotic systems have been developed previously for endoscopic intervention, many issues have been identified that hinder their clinical translation, including high system complexity, coupled motion between segments in the arms, and lack of robust haptic-based controller. ***The proposed dexterous endoscopic robot, which is already a significantly less complex system, also addresses these concerns. Its two segments will be decoupled through purposeful design based on a novel mechanics model to increase motion accuracy. The integration of hysteresis compensation and the Fiber Bragg Grating (FBG)-based force sensor as feedback in its controller ensures more accurate and safe control. The robot, miniaturized to fit inside the instrument channel of a regular colonoscope, will directly replace the existing manually-operated ITknife 2 and thus create minimal disruption to the standard procedure workflow, leading to an increase in its potential for clinical translation.***

PROJECT OBJECTIVES AND LONG-TERM IMPORT:

1. To develop a novel multi-degree of freedom (DoF) dexterous endoscopic robot for endoscopic submucosal dissection (ESD) in the colon.
2. To develop an accurate mechanics-based kinematic model for robot design optimization.
3. To characterize hysteresis in the flexible robot body to improve control accuracy.
4. To develop a force-compensated position controller for the robot based on Fiber Bragg Grating (FBG) force feedback.
5. To experimentally evaluate the performance of the dexterous endoscopic robot in benchtop experiments and colon phantom.

Key issues with existing manual ESD instrument:
1. Limited degrees of freedom affects distal dexterity needed to perform ESD
2. Unstable visualization due to the need to manipulate the colonoscope during ESD
3. Coordination between two clinical personnel in performing ESD affects negatively their efficiency and performance

Key issues with existing flexible endoscopic robots, all still under research:
1. High undesired system complexity with their dual-arm configuration
2. Oversized for the 3.2mm instrument channel in standard colonoscope for ESD
3. Coupled motion that affects motion accuracy
4. Lack of haptic feedbacks

Immediate significance of the research outcome
The proposed dexterous robot design, modeling, and hysteresis and force error-compensated control will lead to:
1. More accurate and dexterous control of the instrument during ESD
2. Stable endoscopic visualization
3. ESD by only one endoscopist, improving performance and surgical outcome
4. Safer interaction between the instrument and the inner colon wall due to the force feedback
5. Direct adoption in a standard colonoscope with minimal disruption to current procedure

Long term impacts:
1. Facilitating adoption of dexterous endoscopic robots in other procedures, including skull base surgery and transoral surgery
2. Automating the ESD procedure and colonoscope navigation through shared autonomy that would improve surgical outcome and patient comfort during the procedure
3. Robust integration of complete haptic feedback, including both tactile and kinesthetic sensation in flexible surgical robots

WORK IN PROGRESS

DEVELOPMENT OF A FOLDED BILAYER SCAFFOLD FOR INTESTINAL TISSUE ENGINEERING

Principal Investigator: Professor CHAN Hon Fai[1,2,3,4]
Institute for Tissue Engineering and Regenerative Medicine, Department of Biomedical Engineering, CUHK

Research Team Members:
Hu Meng, Research Assistant [1,2,3,4] (07/2019-12/2019)
Xiaoyu Zhao, Research Assistant [1,2,3,4] (01/2020-06/2019)

[1] Institute for Tissue Engineering and Regenerative Medicine, CUHK
[2] Department of Biomedical Engineering, CUHK
[3] School of Biomedical Sciences, CUHK
[4] Shun Hing Institute of Advanced Engineering, CUHK

Reporting Period: 1 July 2019 – 30 April 2020

INNOVATION AND PRACTICAL SIGNIFICANCE:

To include a paragraph to highlight specifically the innovation and practical significance of your work. Both VC and the door would like to see more research endeavors be directed to innovation and technology transfer for the betterment of mankind.

The major innovation of the current work lies in the design of the folded bilayer hydrogel scaffold. All scaffold materials reported previously for the production of TESI consist of single-phase materials such as polylactic-co-glycolic acid (PLGA), poly-ε-caprolactone, chitosan etc, without taking into consideration the distinct properties of different layers of the intestinal wall. Decellularized tissue is an exception but its application is limited by human tissue source. The bilayer hydrogel scaffold is expected to outperform current designs by better recapitulating the multi-layered structure of small intestine. In addition, we are the first group demonstrating the fabrication of a folded scaffold by mechanics-guided folding, which represents a new paradigm in tissue engineering. The technique is novel but at the same time simple for scale-up production. We will file a patent application on the scaffold materials and fabrication technique after they are optimized, and actively pursue preclinical and clinical trial to bring the potential therapy to patients.

ABSTRACT

Short bowel syndrome can be caused by birth defect or surgical removal of part of the intestine resulting from a number of diseases. It is associated with high morbidity and mortality. Current therapies are mostly ineffective, ultimately requiring an intestinal transplant but complications arise. Construction of tissue-engineered small intestine (TESI) in vitro, in which patient cells are cultured on a biomaterial scaffold, offers a therapeutic alternative. However, the current scaffold designs do not take into consideration the distinct properties of different layers of the native intestine wall. In addition, the dense mucosal folds, which are present along the inner surface of intestine and assume an important functional role, have not been reproduced. Recently, we have engineered a folded bilayer hydrogel scaffold with tunable mechanical properties via a theory- and simulation-guided approach for the first time. A soft and stretchable hydrogel is stretched before a relatively stiff

hydrogel is layered on top. Subsequent relaxation induces controlled folding of the top layer, and the process is reversible. To further develop the strategy for clinical translation, we propose to 1) optimize the properties of the bilayer hydrogel scaffold including pore size, stiffness, and adhesion between two layers; 2) direct the differentiation of primary intestinal organoid in the bilayer scaffold. The successful completion of the project will improve the current design of TESI and advance the field of intestinal tissue engineering.

1. OBJECTIVES AND SIGNIFICANCE

Short bowel syndrome (SBS) affects 3-4 individuals per million people[1]. A number of conditions can lead to SBS, such as congenital anomalies and intestinal resection following Crohn's disease. Since SBS can cause malabsorption and malnutrition, it is associated with high morbidity and mortality, especially in children in which the estimated 5-year mortality approaches 40%[2]. Current therapies aiming to increase absorption or restore intestinal length are ineffective. Intestinal transplantation is the last resort but is limited by tissue supply and complications such as graft rejection[3].

The development of a tissue-engineered small intestine (TESI) by incorporating patient's own intestinal cells (e.g. organoid unit derived from intestine tissue) into a scaffold represents an attractive option for autologous transplantation[3]. However, none of the reported TESI has been applied in clinic so far. Possible reasons include a lack of control of organoid differentiation and complications arising from multiple surgeries required for the *in vivo* maturation of TESI[4]. Generating TESI resembling native intestine *in vitro* without the need for *in vivo* maturation would be advantageous. Nevertheless, the current scaffold fabrication approaches fail to recapitulate mucosal fold, which increases surface area for absorption and endows the intestine with the flexibility to contract and expand, and mimic the properties of distinct layers of the intestine wall, consisting mainly of mucosa, submucosa, muscle layers and serosa. Our lab has recently demonstrated the fabrication of a folded bilayer hydrogel scaffold, mimicking the architecture of intestinal fold, based on the concept of surface instability[5].

To further develop the strategy for clinical translation, we will achieve the following aims.
Aim 1: Optimize the properties of the bilayer hydrogel scaffold including pore size, stiffness, and adhesion between two layers;
Aim 2: Direct the differentiation of primary intestinal organoid (containing intestinal stem cells and the supporting mesenchyme) in the bilayer scaffold by applying mechanical and biochemical cues.

We expect to identify a scaffold formulation with optimal pore size, stiffness and adhesion property for organoid culture, and apply cues to direct organoid to differentiate into different intestinal cell types at appropriate location.

2. RESEARCH METHODOLOGY

Aim 1: Optimize the properties of the bilayer hydrogel scaffold including pore size, stiffness, and adhesion between two layers

In this project, we will fabricate our folded bilayer scaffold using poly(ethylene glycol) diacrylate/polyacrylamide and alginate (base hydrogel) and gelatin methacrylate (top hydrogel) based on our established protocols[5]. Following our protocol, we will develop a soft and stretchable base hydrogel. While the base hydrogel is under tension (e.g. 100, 200%), the top hydrogel, which is stiffer, will be added before tension is released to generate the folds. Finite element method will be used to predict and guide the fold formation. To improve the adhesion between two layers, we will devise alternative strategies such as utilizing coupling agents such as 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide and N-hydroxysulfosuccinimide for covalent bonding. To facilitate cell infiltration, we will adjust pore size via changing the biomaterial concentration. Scanning electron microscopy will be used to estimate pore size. Organoids, which will be isolated from mouse intestine according to established protocol[6, 7], will be seeded onto the scaffold and confocal microscopy imaging will be carried out to determine the extent of cell infiltration into the bilayer scaffold. Finally, the hydrogel stiffness, measured via a tensile test, will be tuned by modulating the crosslinking density to optimize cell attachment and viability. Expected result: A folded bilayer hydrogel scaffold with optimized properties for cell culture.

Aim 2: Direct the differentiation of primary intestinal organoid in the bilayer scaffold by applying mechanical and biochemical cues

We will investigate whether the distinct mechanical stiffness (top: stiff, bottom: soft) of our optimized scaffold can direct organoid to differentiate into various layers. For example, we will look for formation of villus and crypt, markers of different cell types found in different layers, as well as functional brush-border enzymes in the epithelium. To enhance the differentiation efficiency, we will consider introducing growth factors either in free form or encapsulated in microparticles in the hydrogel scaffold for sustained release of biochemical cues to promote differentiation along a specific lineage. For example, transforming growth factor β1 will be impregnated in the base hydrogel to stimulate the differentiation into smooth muscle layer[8]. Expected result: Controlled organoid differentiation into intestine-like tissues in the folded bilayer scaffold.

3. RESULTS ACHIEVED SO FAR

3.1. Mechanics-guided folding

Based on the concept of mechanical/surface instability (Fig. 1A), we fabricated the folded bilayer scaffold by first stretching polyacrylamide/alginate or poly(ethylene glycol) diacrylate hydrogel before coating the surface with a layer of gelatin hydrogel. After relaxation of the bottom layer, folding pattern is produced which resembles the structure of porcine intestine (Fig. 1B). The pattern dimension (e.g. wavelength (ω) and amplitude (A)) is tunable and is controlled by the pre-stretch ratio (λ) and thickness of the top layer (H_f) (Fig. 1C-D). Reversible folding-unfolding can be achieved to recapitulate the change in mucosa shape during intestine movement (e.g. peristalsis) (Fig. 1E).

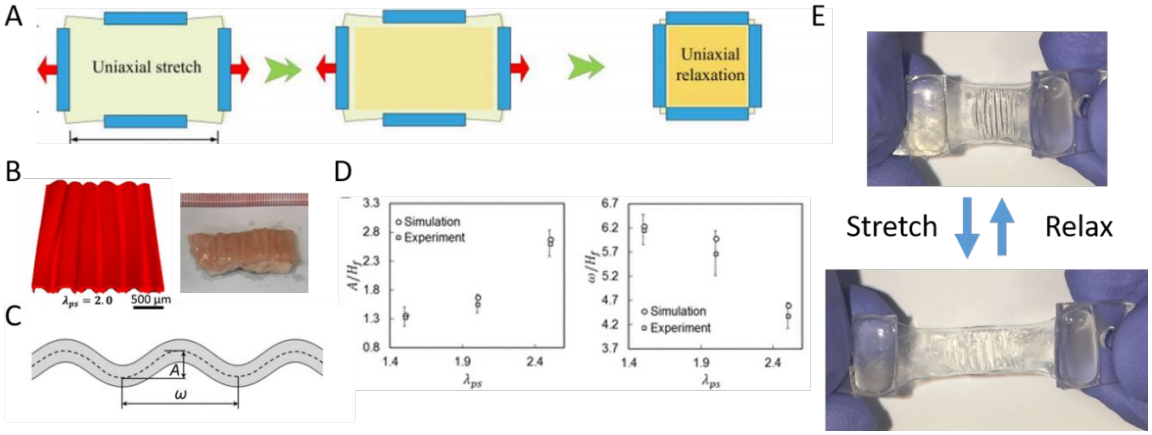

Figure 1. Fabrication and characterization of folded bilayer hydrogel scaffold. (A) Schematic diagram showing folded scaffold formation. (B) Confocal image of scaffold and an image showing a section of the porcine intestine. (C) Schematic diagram indicating the parameters of scaffold. (D) Comparison of simulation and experimental results on the pattern amplitude and pattern wavelength of the folded scaffold. (E) Reversible folding-unfolding triggered by stretching and relaxing the scaffold.

3.2. Optimization of material choice, adhesion between two materials, stiffness and pore size

In our previous work, we observed delamination of top hydrogel (gelatin) after prolonged cell culture, which led to distortion of folding pattern (Fig. 2A). Besides, mechanical stiffness and pore size of the hydrogel are not optimized for organoid culture. To address this issue, we have devised a new strategy to fabricate the folding pattern, in which alginate hydrogel was crosslinked on top of the stretched polyacrylamide/alginate hydrogel so that the alginate molecules will serve as a linkage between two layers (Fig. 2B). We have successfully showed a stronger adhesion between the two layers, even after soaking in culture medium for 4 days (Fig. 2C). In terms of mechanical stiffness, we have performed mechanical testing on alginate of different concentrations, and observed stiffness increasing from 10 to 60 kPa as alginate concentration increased (Fig. 2D). SEM images showed smaller pore size in alginate of higher concentration (Fig. 2E). As the next step, we will test the effect of stiffness and pore size on organoid proliferation and differentiation.

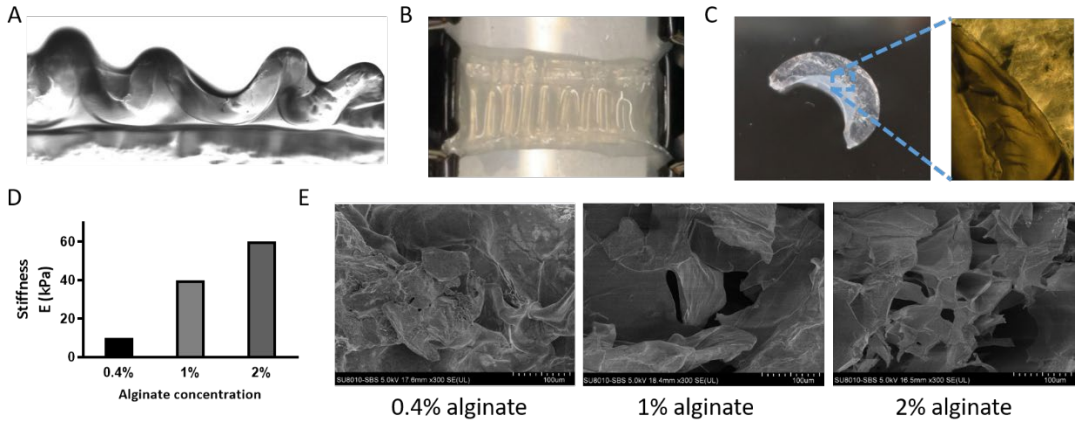

Figure 2. Optimization of scaffold properties. (A) Delamination of top hydrogel (gelatin) after prolonged culture. (B) Folded bilayer scaffold fabricated with alginate hydrogel on top. (C) Adhesion of two layers observed after prolonged culture. (D) Mechanical stiffness of alginate scaffold of different concentrations. (E) SEM images showing pore size of alginate scaffold of different concentrations.

3.3. Intestinal organoid culture

We have begun culturing intestinal organoid by isolating intestinal crypt from mouse following established protocol[7]. Briefly, mouse intestine was isolated and washed twice with PBS. Villi were carefully scrapped off and the remaining part was cut into small pieces and incubated in EDTA for 40 min. Afterwards, the small pieces were suspended in PBS and passed through a 70 μm cell strainer. The collected organoids were centrifuged and embedded in Matrigel for culture. Preliminary data showed that the organoids were viable after culture for 12 days (Fig. 3).

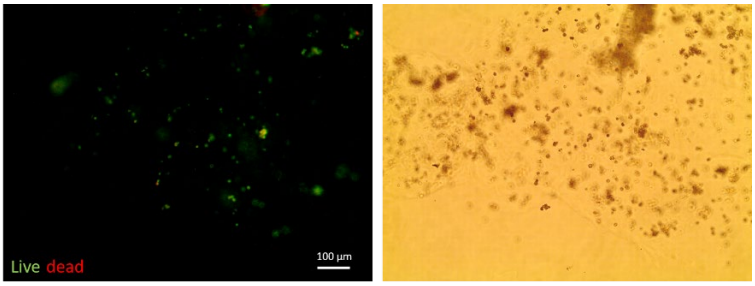

Figure 3. Live-dead staining and bright field images of mouse intestinal organoid after culture for 12 days.

3.4. Potential for research collaboration, commercialization and technology transfer

We have established a research collaboration with Prof. Hans Gregersen (Department of Surgery, CUHK) to study how mechanical forces affect organoid culture. Prof. Gregersen is a pioneer in gastrointestinal biomechanics and has shown that residual strain/stress was present in non-loaded intestine. We will adopt our bilayer folded hydrogel scaffold to investigate how mechanical forces generated in the system, which will be optimized to mimic the *in vivo* condition, influence organoid proliferation and differentiation. For commercialization and technology transfer, we aim to file a provisional patent after the properties of the bilayer scaffold are optimized and actively look for commercialization opportunities such as developing *in vitro* intestinal model for drug screening.

4. PUBLICATION AND AWARDS

4.1. Award

1. **H.F. Chan**, "Young Scholar Award", World Association for Chinese Biomedical Engineers (2019)

4.2. Conference presentation

1. **H.F. Chan**, R. Zhao, G. Parada, H. Meng, K. W. Leong, L. Griffith, X. Zhao, "Development-inspired engineering of folded mucosa guided by mechanics model" 9th WACBE World Congress in Bioengineering, Taipei, Taiwan, August 16-19 (2019)

4.3. Publication

1. Y. Zhu, S. Deng, H. Li, **H.F. Chan**, "Macrophages activated by akermanite/sodium alginate composite hydrogel stimulate migration of bone marrow stromal cells" (in submission)

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WORK IN PROGRESS

OPTOGENETIC REGULATION OF HORMONE PRODUCTION FOR GLUCOSE HOMEOSTASIS MAINTENANCE

Principal Investigator: Professor Liting DUAN
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Research Team Members:
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Reporting Period: 1 July 2019 – 30 April 2020

INNOVATION AND PRACTICAL SIGNIFICANCE:

The generation of cells producing insulin or other related hormones would provide an unprecedented cell source for drug discovery and cell transplantation therapy targeting diabetes. To this end, presented here is a previously unavailable strategy that uses LIGHT to precisely and rapidly control the production of one or two hormones in engineered cells for glucose homeostasis. The novel optical strategy offers many key advantageous over the currently available cell-based methods to balance the blood glucose level (e.g. transplantation of healthy islet cells or stem cell-derived pancreatic cells), including:

1. *Precise control over the production of the related hormones with high spatial and temporal resolution*
2. *Fast on-and-off switch of the hormone production*
3. *The capacity to bidirectional influence glucose homeostasis by orthogonally inducing the production of two hormones with opposite effects on the blood glucose concentration*
4. *Good scalability*

Therefore, the proposed strategy will have a broad appeal to the pharmaceutical and clinical sectors targeting diabetes.

ABSTRACT

Diabetes is a progressive and complex disease featured by chronically deregulated blood glucose levels affecting more than 422 million people in the world. In Hong Kong, one in ten people suffer from diabetes, and the prevalence will continue to increase due to the rapid growth of the aging population. Aberrant insulin production is a hallmark of both type 1 and type 2 diabetes. Since no cure is available yet, current treatment strategies include strict food control along with lifelong regular injections of insulin. Many research efforts are devoted to developing alternative methods to increase insulin concentration for diabetic patients. Novel methods that enable precisely controlled and rapid production of hormones regulating blood glucose levels hold great promise to provide effective treatments. Here we propose to design and construct optogenetic systems that use light to control the production of blood glucose regulating hormones. We expect light-inducible production of insulin or glucagon-like peptide can offer a promising approach to treat diabetes. Besides, we plan to establish an orthogonal optogenetic system to express different hormones under the light stimulation of different wavelengths. We expect the proposed orthogonal system will be able to balance blood glucose level bidirectionally, thus presenting a great tool

to study the glucose homeostasis and the mechanisms underlying diabetes.

1. OBJECTIVES AND SIGNIFICANCE

1.1. Objectives

1. To develop optical control of insulin production in living cells as a potential treatment for type 1 diabetes
2. To develop optical control of glucagon-like peptide (GLP) production in living cells as a potential treatment for type 2 diabetes
3. To develop an orthogonal optogenetic system to independently produce insulin (or GLP) and glucagon for bidirectional maintenance of blood glucose level

1.2. Significance:

The generation of cells producing insulin or other related hormones would provide an unprecedented cell source for drug discovery and cell transplantation therapy targeting diabetes. To this end, presented here is a previously unavailable strategy that uses LIGHT to precisely and rapidly control the production of one or two hormones in engineered cells for glucose homeostasis. The novel optical strategy offers many key advantageous over the currently available cell-based methods to balance the blood glucose level (e.g., transplantation of healthy islet cells or stem cell-derived pancreatic cells), including (1) Precise control over the production of the related hormones with high spatial and temporal resolution; (2) Fast on-and-off switch of the hormone production; (3) The capacity to bidirectional influence glucose homeostasis by orthogonally inducing the production of two hormones with opposite effects on the blood glucose concentration; (4) Good scalability.

2. RESEARCH METHODOLOGY

Many optical approaches for regulating gene expression have been established based on photo-mediated protein-protein interactions (Figure 1A). Protein A and B will bind to each other upon light illumination. Such light-gated hetero-dimerization allows the optical reconstitution of split transcription factors, where A is fused to DNA binding domain (DBD) and protein B is coupled with transcriptional activation domain (AD). Light stimulation dimerizes DBD and AD, which reconstitute the transcription factors and drive the expression of the gene of interest located after the promoter region.

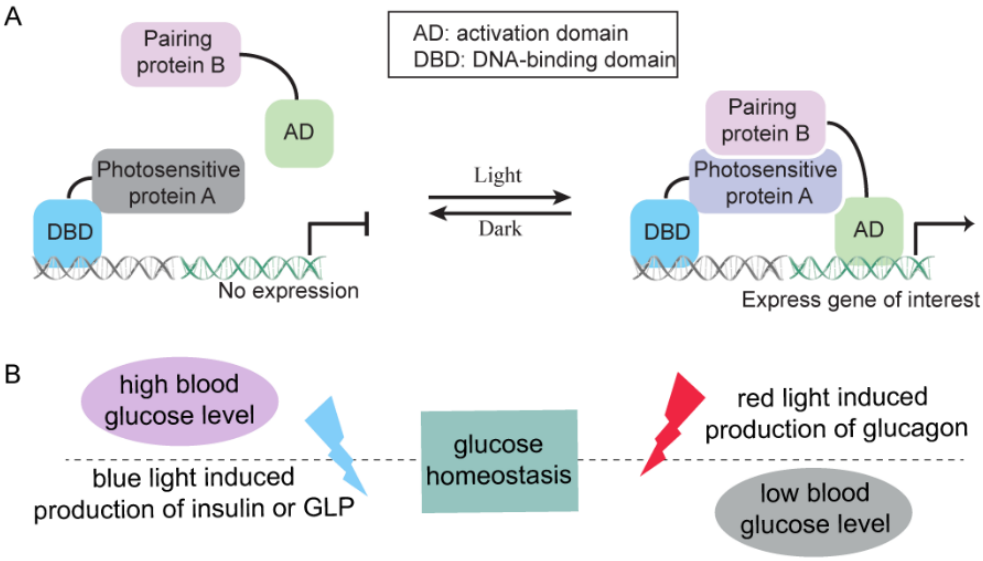

Figure 1. (A) The design of light-induced gene expression system. (B)The design of the orthogonal system to produce insulin and glucagon for directional maintenance of glucose homeostasis.

Task 1: To develop optical control of insulin production in living cells

In this task, we will construct optogenetically controlled expression and production of insulin in engineered mammalian cells as a potential cell transplantation therapy to treat type 1 diabetes. We will adopt an optical strategy that uses blue light to induce the production of the target protein. The sequence of insulin will be incorporated into the system. HEK293T cells will be used to express the designed optogenetic system. The cell culture medium will be collected after transfected cells undergo 1-day blue light stimulation. The insulin level in the medium will be assayed by ELISA.

sk 2: To develop optical control of glucagon-like peptide (GLP) production inside cells

In this task, we will develop an optogenetic system to optically induce the production of glucagon-like peptide (GLP) in engineered mammalian cells as a potential therapy to treat type 2 diabetes. Here we propose to use light to induce the production of GLP in cells to maintain the glucose homeostasis. Similar to the strategy described in Task 1, the sequence encoding a short variant of human GLP-1 (GLP-1) will be inserted into the light-inducible gene expression system. Genetically engineered HEK293T cells will be generated that are transfected with this optogenetic system. The level of secreted GLP-1 will be assayed after cells are subject to 24-h blue light stimulation.

Task 3: To develop an orthogonal system to produce insulin and glucagon for bidirectional regulation of blood glucose level

In task 3, we plan to develop an orthogonal system that the secretion of insulin (or GLP) and glucagon can be separately controlled by light of different wavelengths. We will utilize a red light-induced gene expression system to trigger the expression of glucagon. HEK293T cells will express both the optical-controlled insulin (or GLP) production system (described in Task 1 and 2) and the optical-regulated glucagon secretion system (Figure 1B). Blue light required for the expression of insulin (or GLP) (450 nm) is very well separated from the red light (660 nm) indispensable for light-triggered production of glucagon, which allows independent optical control over the production of different hormones.

3. RESULTS ACHIEVED SO FAR

3.1. Optimization of the experimental conditions for light-gated gene expression

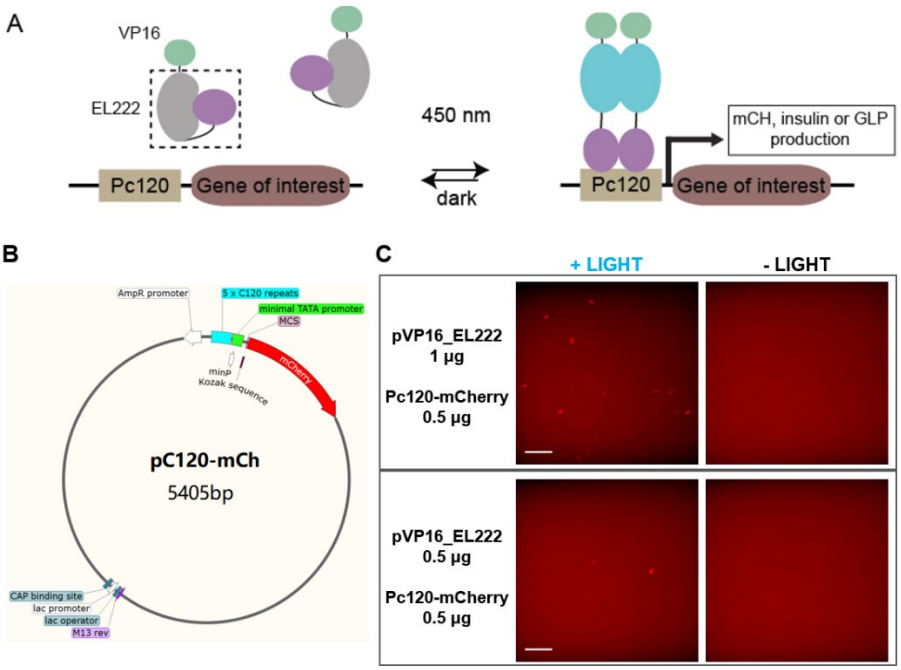

Figure 2. (A) The design of blue light-induced protein expression system. (B) The DNA plasmid map for pC120-mCh. (C) Optimization of transfection conditions shows that 2:1 ratio significantly increases the efficiency of light-induced protein expression.

We have optimized the experimental procedures for the blue light-gated gene expression system, including the light illumination conditions and cell transfection. We have adopted a light-inducible transcription system that has been demonstrated to utilize a bacterial light-oxygen-voltage protein (EL222) to bind DNA upon blue light illumination. After DNA is conjugating with the EL222-binding sites, the gene inserted after a minimal promoter will be expressed (Figure 2A). To examine how the light-controlled gene expression system work in our experimental settings, we constructed a light-inducible mCh expression system that can initiate the production of mCh upon blue light stimulation (Figure 2B). In this plasmid, the mCh sequence (717 bp) was placed downstream of pC120 promotor. The level of mCh expression can be easily assayed in living cells by a fluorescence microscope without any additional treatment.

We tested two light illumination conditions. 3T3 cells were plated in 6-well plates and transfected with 0.5μg pVP16-EL222 and 0.5μg pC120-mCh. Using 200 μW/cm^2, intermittent light stimulation (460 nm) with 5 sec on/5 sec off patterns for 24 hr, there was little expression of mCh detected. Instead, we increased the light intensity to 800 μW/cm^2 and changed the illumination pattern to continuous mode. The production of mCh can be detected in a few cells, which indicated that more light exposure (800 μW/cm^2, continuous) is needed to initiate noticeable gene expression. Next, we increased the ratio between the amount of pVP16-EL222 and pC120-mCh varied from 1:1 to 2:1. With the transfection ratio 2:1, more cells expressed a higher amount of mCh than that of transfection ratio 1:1 (Figure 2C). In conclusion, 800 μW/cm^2 continuous blue light stimulation and 2:1 ratio transfection will be used for the light-trigger protein expression.

3.2. The DNA plasmids for blue light-gated insulin or GLP production systems

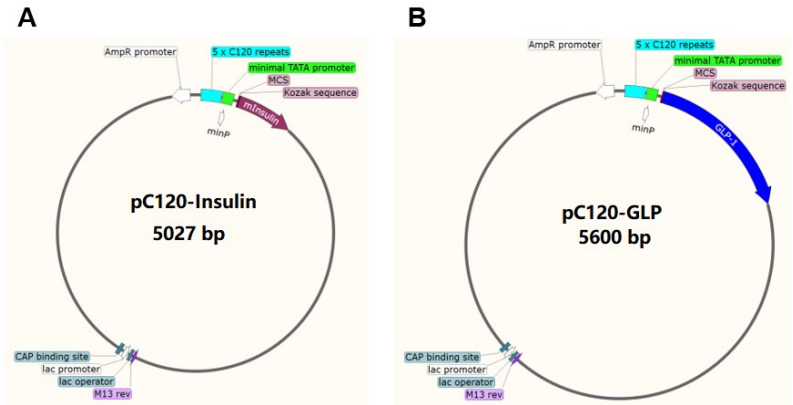

Figure 3. The DNA plasmid map for blue light-inducible expression of insulin(A) and GLP (B).

We have constructed DNA plasmid maps for light-inducible expression of insulin or GLP. The DNA sequence encoding for murine insulin (333 bp) or GLP-1 (906 bp) is inserted after the promoter pC120. In the next stage, we will express pVP16-EL222 and pC120-mCh in HEK293T cells to confirm and evaluate the efficacy of producing insulin or GLP induced by red light.

3.3. The DNA plasmids for red light-gated glucagon production systems and bidirectional expression of insulin and glucagon

We have designed DNA plasmids for red light-inducible expression of glucagon. We will take advantage of red light-induced association between PhyB and PIF6 to induce the reconstitution of a functional transcription factor, which thereby drives the expression of gene residing after the promoter (Figure 4A). The DNA sequence encoding for glucagon (87 bp) is designed to reside after the promoter pCMVmin. In the next stage, we will express the PCMVmin-Glucagon together with TetR-PIF6 and VP16-PhyB in HEK293 cells to confirm and evaluate the efficacy of producing glucagon induced by red light.

Combining the plasmids constructed in Results 3.2 and 3.3, the orthogonal system to independently

produce insulin and glucagon can be achieved. Next, we will validate and examine the bidirectional expression of insulin and glucagon in HEK293 cells.

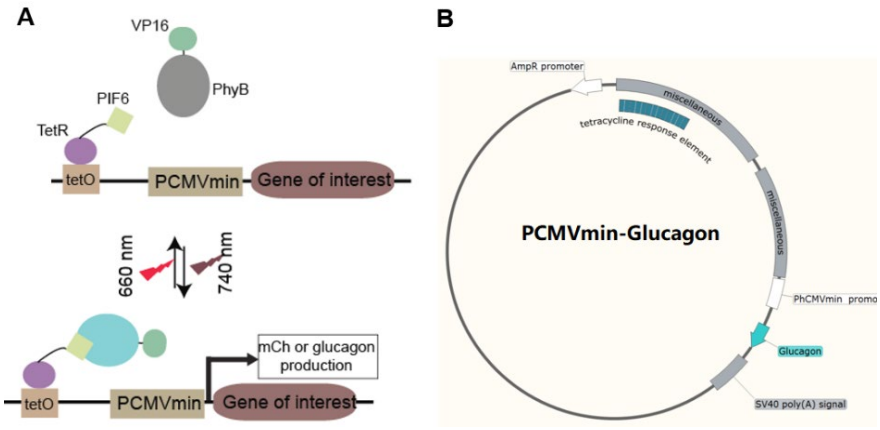

Figure 4. (A) The design of red light-induced production of the target protein. (B) The DNA plasmid map for red light-inducible expression of glucagon where the DNA sequence for glucagon is placed downstream of the PCMVmin promoter.

4. PUBLICATION AND AWARDS

J[1] P. Huang, A. Liu, Y. Song, J.M. Hope, B. Cui, L. Duan*, “Optical activation of TrkB signaling”, Journal of Molecular Biology, [2020] link * denotes the corresponding authors

WORK IN PROGRESS

DEVELOPMENT OF HIGHLY SENSITIVE QUANTITATIVE PHASE MICROSCOPY FOR LABEL-FREE IMAGING OF NEURONAL NETWORK ACTIVITIES

Principal Investigator: Professor Renjie ZHOU
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Co-Investigator: Prof. Vincent Chi Kwan Cheung [(2)]

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Reporting Period: 1 July 2018 – 30 April 2019
(to be completed in June 2020)

INNOVATION AND PRACTICAL SIGNIFICANCE:

The development of optical recording techniques for mapping action potentials is important as it offers many key advantageous over the traditional electrophysiology techniques (e.g., patch clamping), such as:

a. *Noninvasiveness without physical contacts,*
b. *Spatial and temporal resolvability,*
c. *High-throughput measurement capability.*

However, label-free optical imaging techniques (i.e., without using fluorescent tags), that do not suffer from photobleaching and slow kinetics of fluorescent proteins, still have not been developed for long term and high speed recording of action potential signals on excitable mammalian cells. Among possible label-free techniques, interferometric microscopy, particularly the quantitative phase microscopy (QPM), is promising in satisfying the sensitivity and speed requirements needed for imaging action potentials. The PI, Prof. Renjie Zhou who is an expert on QPM, has recently implemented MEMS-based mirrors and highly sensitive cameras into QPM systems. He recently co-developed a theory for understanding the phase noise limit in such systems, which has led to achieve 10-4 temporal sensitivity with 10 ms temporal resolution in a QPM system. In order to image neuronal action potentials as proposed in this project, we need to further achieve 10-5 temporal sensitivity and 1 ms temporal resolution. Therefore, we will develop a QPM system that integrates the following technical innovations:

a. *A high stable interferometric microscopy design,*
b. *A better usage of the dynamic range of a high well-depth camera,*
c. *Capability of operating in the reflection-mode QPM system to inheritably provide 10x better sensitivity.*

Our system will enable us to image, for the first time, the electrical activities of cultured neurons, such as those from induced pluripotent stem cells, without fluorescence labeling. This work will promote strong collaborations with the School of Biomedical Sciences at CUHK through the Co-I Prof. Vincent Cheung who is a neurobiologist. By mapping the neural network activities of

multicellular organisms, e.g., Caenorhabditis elegans, it will establish our technique as an important neural imaging tool for revealing functional maps of complex nervous systems in the future.

ABSTRACT

The challenge in neuroscience lies in the ability to monitor neuronal network activities to study mechanisms of increasingly complex behaviors under normal and disease conditions. These demands of neuroscience can only be met by developing novel microscopy technologies that can image at single neuron levels. Neuronal network activities are characterized by electrical impulses called the action potentials, which has been mapped with fluorescence-based imaging techniques using bright voltage-sensitive dyes. However, such methods suffer from photobleaching of the fluorescent proteins, preventing them for long-term neuronal network functional studies. Therefore, the development of a label-free optical imaging technique (i.e., without using fluorescent tags) is critical in solving this issue. During this project, we propose to develop a highly sensitive interference microscopic technique for imaging the action potential signals in neuronal networks. In the first phase, we have developed a quantitative phase microscope (QPM) and tested its imaging performance. To demonstrate the feasibility in using our QPM system for neural imaging, we have tested its sensitivity with different types of cameras. We have also worked on achieving phase cancellation which can be further used to improve the sensitivity of our system. For the next stage, we plan to use our system for imaging primary neurons, as well as those induced from pluripotent stem cells. If we can successfully image the action potentials in a label-free setting (no one has succeeded so far), this will be a major milestone that will enable many important discoveries in neuroscience.

1. OBJECTIVES AND SIGNIFICANCE

We aim to develop a QPM system that integrates the following technical innovations:

a. A highly stable interferometric microscopy design,
b. A better usage of the dynamic range of a high sensitivity camera.
c. A further improvement of sensitivity by wave-front shaping and phase cancellation.

With this QPM system, we will image the electrical activities of neurons, such as those from induced pluripotent stem cells or primary neurons, without fluorescence labeling.

2. RESEARCH METHODOLOGY

As a foundational step, we will build a QPM that is mechanically stable. Diffraction phase microscopy (DPM) system has been well proven to be one of the most stable QPM systems. There will be several modifications to a regular DPM system (as illustrated in Fig.1) to allow for breaking the hardware limit on temporal sensitivity. At first, a spatial light modulation (SLM) based wavefront shaping system will be built before sample illumination for phase cancellation. MEMS mirror based SLMs in general have higher mechanical stability (~ 10^{-6}) compared with liquid crystal-based SLMs (~10^{-3}), thus can be a better choice for canceling the phase of the sample without adding substantial noise. In order to do that, a flat wave-front will be first projected on the SLM and then the phase of the sample will be measured with a camera. After that, the inverse phase of the sample will be projected on the SLM before its phase is measured again. At the end, we expect to measure a relatively flat phase that indicates the sample is "concealed". Preliminary results in Fig. 2 have demonstrated this principle, where the phase of a 10 μm polystyrene bead has been cancelled. During the initial test, a liquid crystal based SLM is used, but the same procedure can be directly applied to MEMS mirror based SLM for high mechanical stability. The second modification is that we applied a super-high well depth camera with an electron well depth of more than 2 million to achieve sub-nano sensitivity.

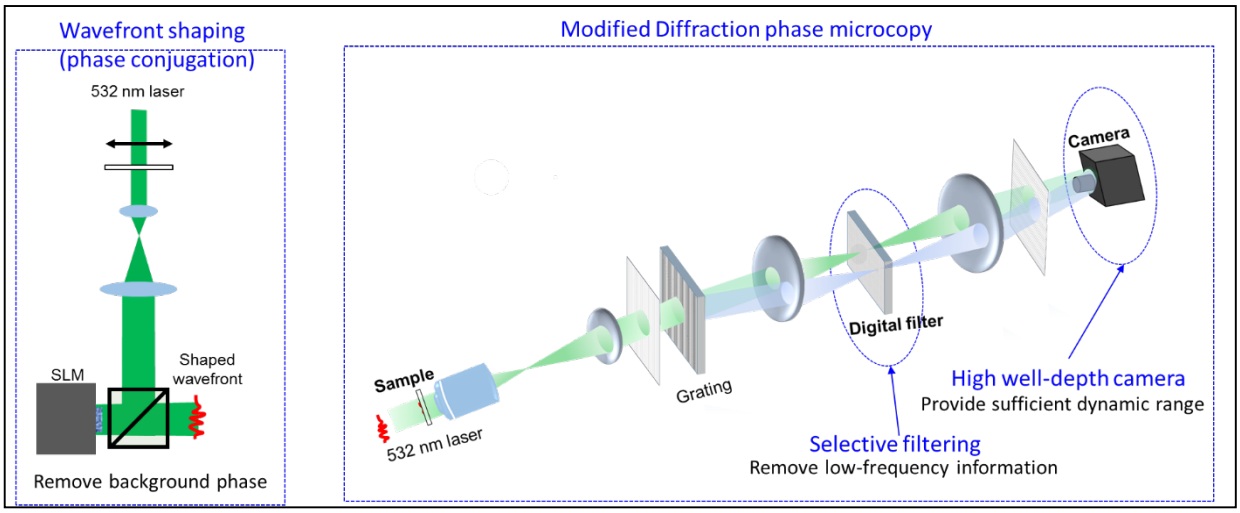


Fig. 1. Proposed design of the highly sensitive QPM system.

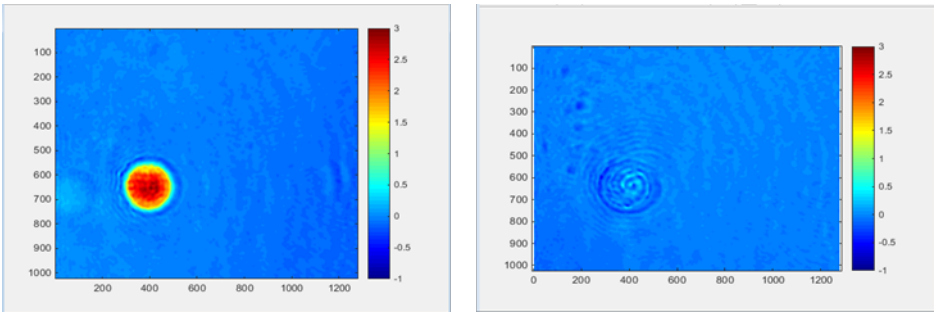


Fig. 2. Cancellation of the phase of a 10 μm bead.

3. RESULTS ACHIEVED SO FAR

3.1 Design and build a versatile common-path quantitative phase microscopy system

Figure 3(a) shows the schematic design, where a fiber-coupled 532nm CW laser with power stability less than 1% is used as the illumination source. Light from the fiber was collimated and focused to a 20× objective and then collimated by the 150 mm focal tube lens. The sample image was projected onto a transmission grating. The first diffraction order was passed unobstructed, while the 0th order was filtered with a 10μm pinhole mask placed in the Fourier plane of a 4-f optical system, consisting of a 35 mm lens and a 150 mm lens. Interferogram were formed on the camera. The actual system that has been constructed is shown in Fig. 3(b).

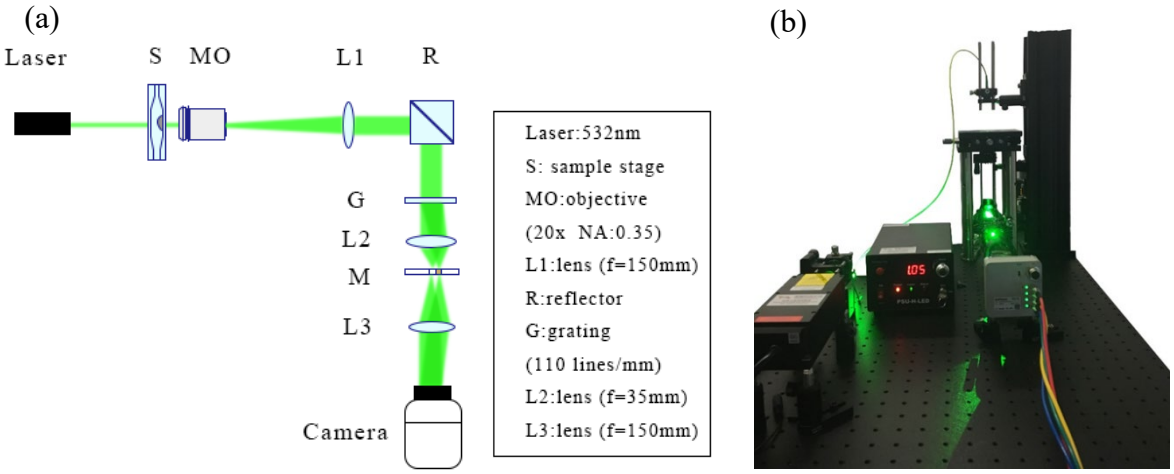
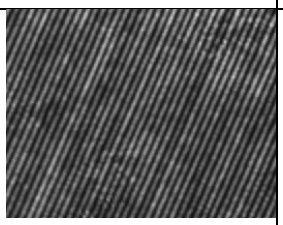
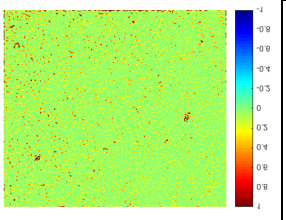
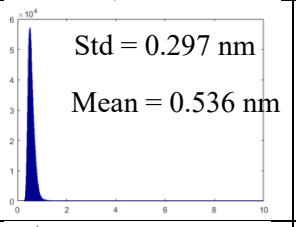
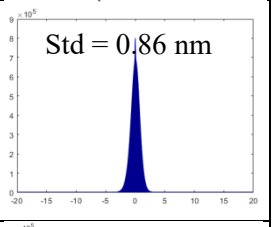
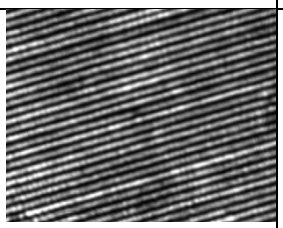
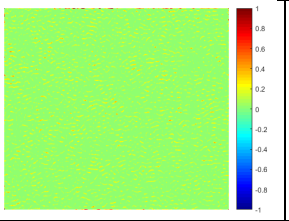
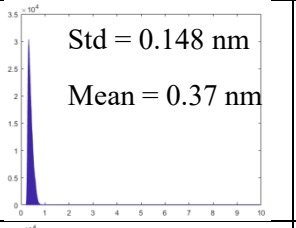
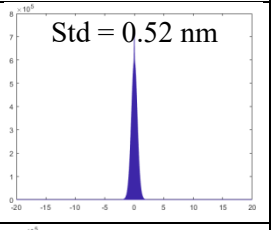
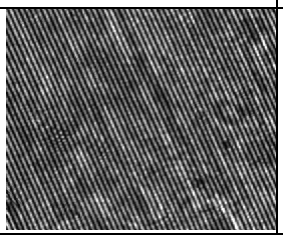
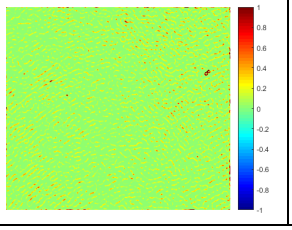
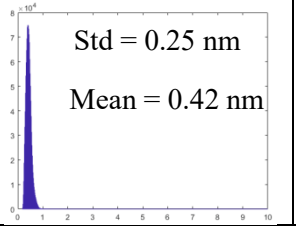
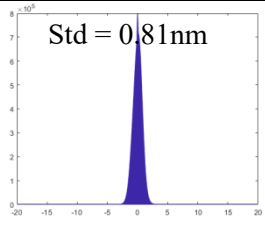


Fig. 3. (a) Schematic design of the QPM system; (b) the photo of the actual QPM system.

3.2 Comparison of sensitivity of different cameras

Table 1. Comparison of camera sensitivity

Camera model	Interferogram	Noise distribution (mrad)	Temporal noise (nm)	Spatial noise (nm)
SMN-B 012-U			 Std = 0.297 nm Mean = 0.536 nm	 Std = 0.86 nm
Flea3 FL3-U 3-32S2 M			 Std = 0.148 nm Mean = 0.37 nm	 Std = 0.52 nm
C1285 R12M			 Std = 0.25 nm Mean = 0.42 nm	 Std = 0.81nm

We have tested our system temporal and spatial noise with different types of cameras, and the results are summarized in Table 1. The noise is characterized through mean and standard deviation (Std) values. As shown, the values of temporal noise are less than 1 nm which indicates a high sensitivity has been achieved by our setup. We are also trying high well depth camera and high-speed camera with spatial and temporal average algorithms to further reduce the noise level.

3.3 Sample Testing

In order to validate the feasibility of our setup, we used standard 5um polystyrene beads for testing. We first capture a calibration image which does not contain the sample to subtract the background from the sample

image. Then we conduct phase retrieval procedure to obtain the phase map as shown in Fig. 4(a). During the procedure, a Fourier transform of the interferogram is obtained as shown in Figure 4(c). For both sample region and background image, a bandpass filter is used to extract the modulated signal, which is then brought back to the baseline. Figure 4(b) indicates the region of interest from Figure 4(a), and a line profile showing the height of sample is drawn in Figure 4(d). The results show that our system can quantitative measure the thickness of sample.

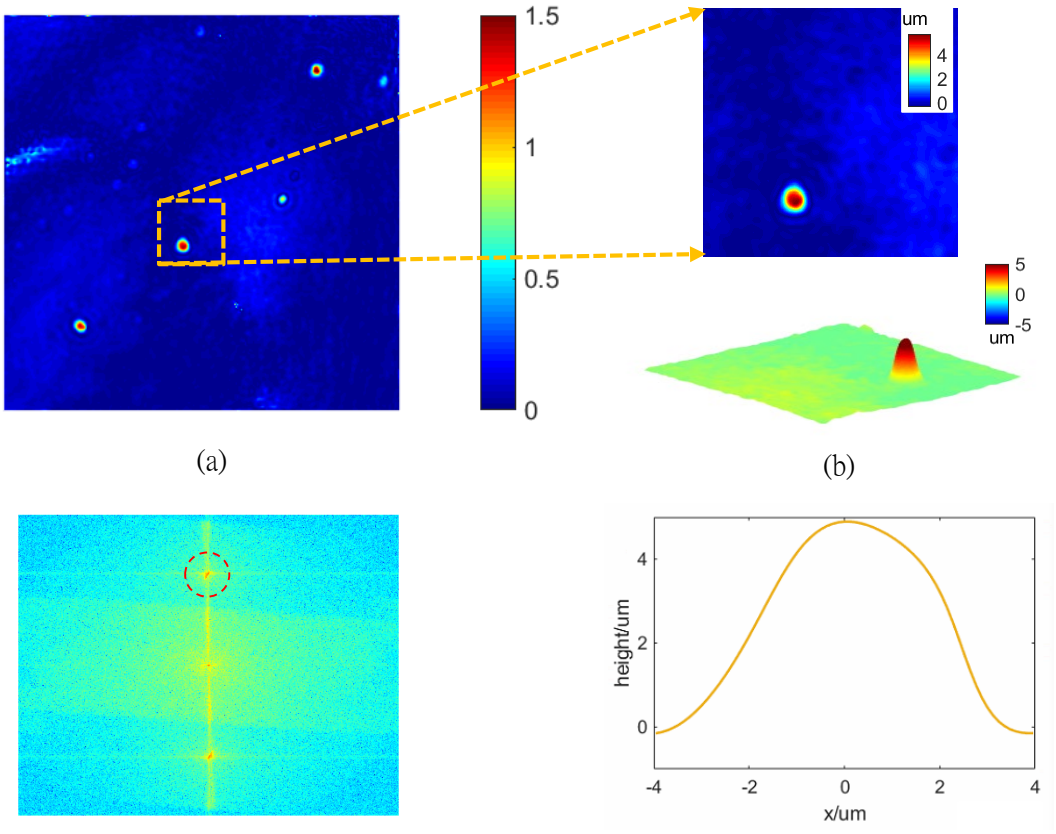


Fig. 4. DPM system validation. (a) Phase map of a captured interferogram; (b) a zoom-in height map of (a); (c) the Fourier spectrum modulus of the interferogram; (d) a line profile of the 5 μm bead.

3.4 Wave-front shaping and phase cancellation

There are several modifications to a regular DPM system to allow for breaking the hardware limit on temporal sensitivity. Here we used an SLM in a digital optical phase conjugation (DOPC) system, which was then integrated with our DPM system for sample phase cancellation (as shown in Fig. 5). This integrated system was developed through a collaboration with Prof. Puxiang Lai's lab (Department of Biomedical Engineering at PolyU).

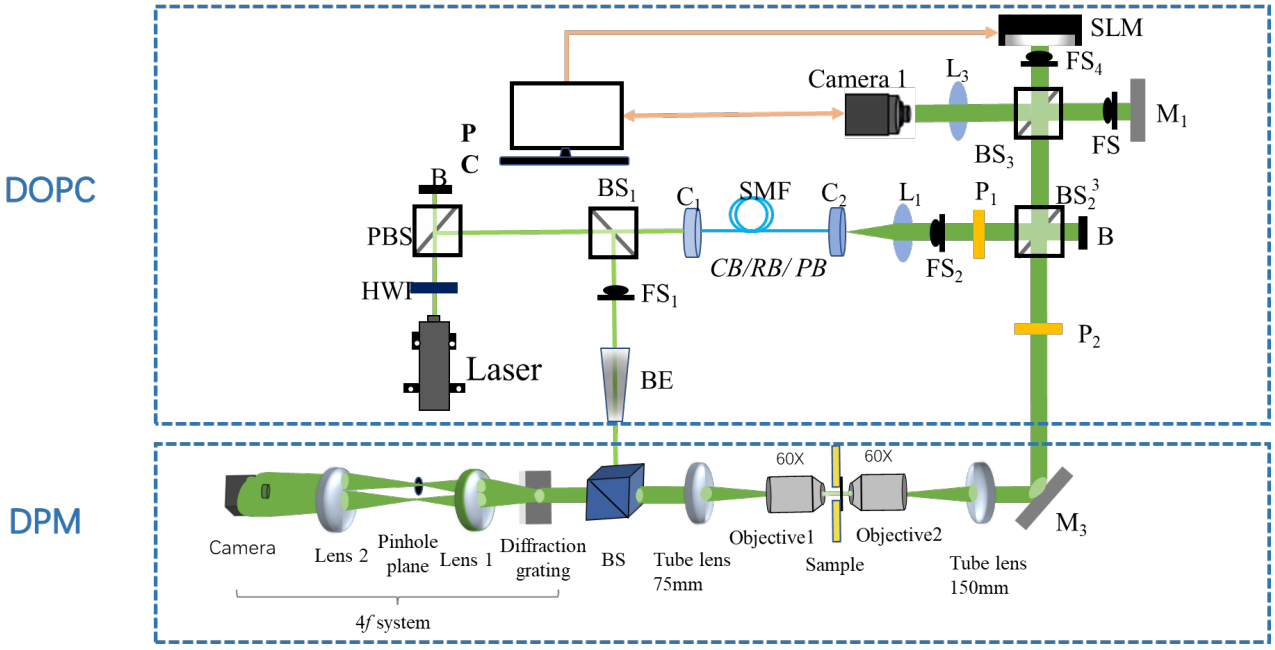


Fig. 5. The integrated system that contains digital optical phase conjugation (DOPC) and DPM.

First, a flat wave-front was first projected on the SLM, and then the phase of the sample is measured by the DPM system. We tested our system by measuring the phase and height map of the 5μm bead (as shown in Fig.6), and the result validated the performance of this integrated system.

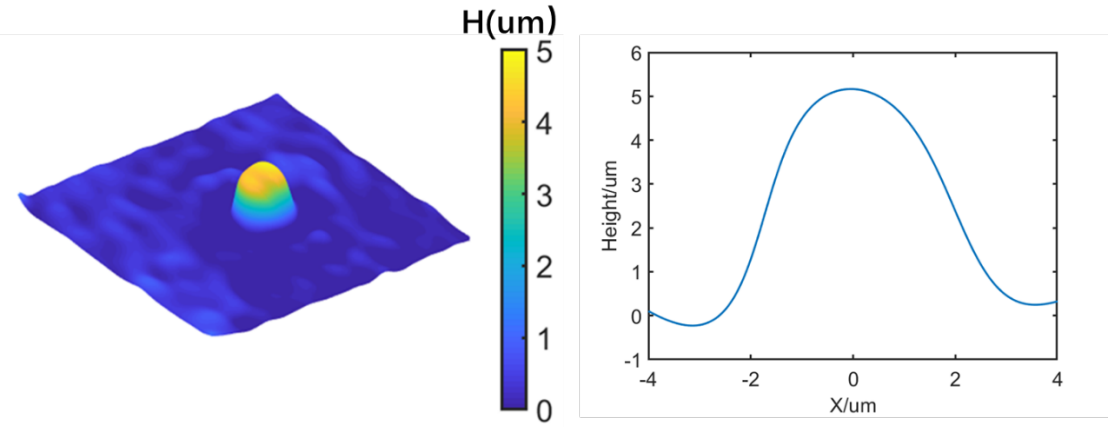


Fig. 6. The height map and line profile images of the 5um beads.

After that, the inverse phase of the sample was projected on the SLM before its phase was measured again with DPM. Finally, a relatively flat phase was measured that indicated the sample is “cancelled”. Figure 7 shows the validation results of achieving phase cancellation of a 5μm bead. We are currently working on implementing this system for imaging biological cells and then neurons.

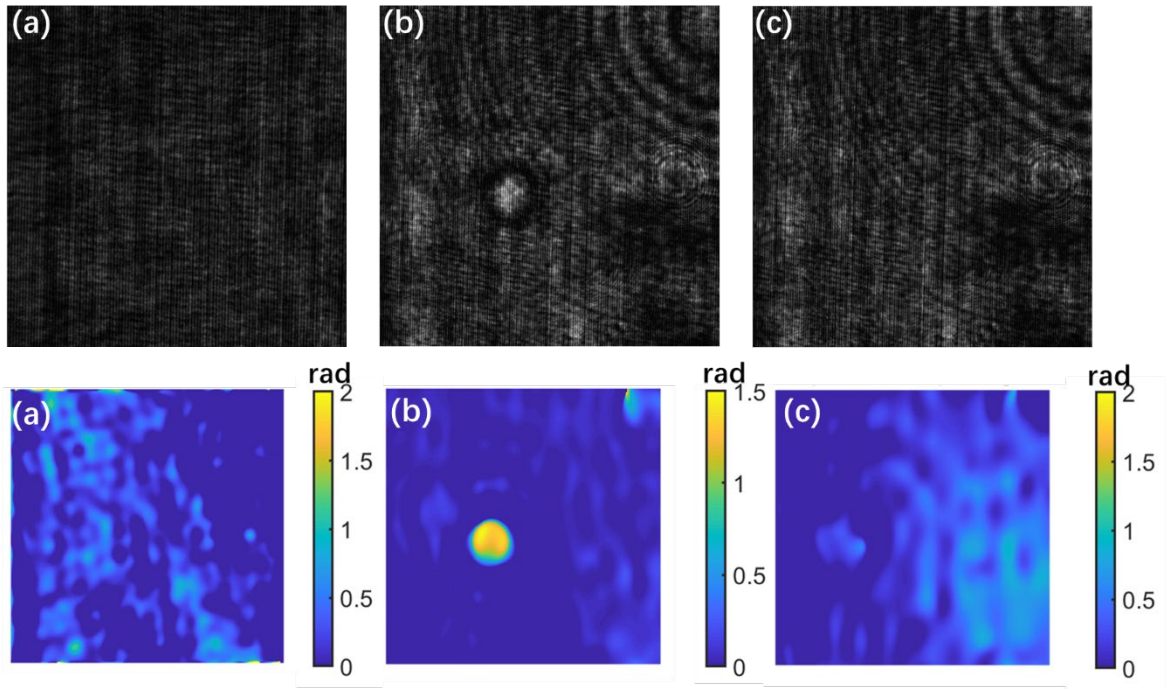


Fig. 7. Validation of using phase conjugation for cancellation the phase of a 5 μ m bead. (a) Background interferogram without sample; (b) interferogram with the sample moved to the field of view; (c) interferogram after conducting the phase conjugation experiment. (d), (e), and (f) correspond to the retrieved phase maps of (a), (b), and (c), respectively.

4. PUBLICATION AND AWARDS

[1] R. Pandey*, R. Zhou*, R. Bordett, C. Hunter, K. Glunde, I. Barman, T. Valdez, and C. Fincke, "Integration of Diffraction Phase Microscopy and Raman Imaging for Label-free Morpho-molecular Assessment of Live Cells," Journal of Biophotonics 12, e201800291 (2019). link * denotes the corresponding authors

COMPLETED

DEVELOPMENT OF A NOVEL ROBOTIC MANIPULATOR FOR CONFINED SPACE SURGERY

Principal Investigator: Professor AU, Kwok Wai Samuel
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Project Start Date: 1 July 2017
Completion Date: 30 June 2019

INNOVATION AND PRACTICAL SIGNIFICANCE:

Although substantial progress has been made, existing flexible instruments still lack synergy among the core surgical enablers including the instrument accessibility, size, and surgical functionalities. The success of this project will provide a new mechanical and control framework for the development of robotic instrument that is capable of overcoming these limitations. This innovative robotic system enables surgeons to provide more accurate, effective, and less invasive procedure even for the complex cases such as skull base surgery, which are currently difficult to treat even with the state-of-the-art robotically assisted surgery. The proposed technology can also allow more patients suitable for and can benefit from MIS in these anatomical regions, ultimately, improving the quality of life of patients

ABSTRACT

Minimally Invasive Surgery (MIS) has been widely adopted in many surgical specialties. Still, for some hardly accessible anatomical regions, only limited options of MIS can be offered by physicians, in particular for orthopaedic surgery. Existing drilling, debridement, and grafting tools for orthopaedic applications are predominantly rigid, preventing the surgeons to access many confined areas and to operate the procedures with sufficient dexterity and accuracy like Anterior Cruciate Ligament (ACL) reconstruction or Core Decompression of the Femoral Head Osteonecrosis and treatment of osteolytic lesions. Having debriding and grafting instruments with high dexterity and robotically assisted can help physicians to access the very difficult to reach areas within the pelvis or knee areas, significantly improving the efficacy in these procedures.

In this project, we developed a 6.5-mm miniaturized, robotic articulated surgical drill to address the lack of dexterity issue and limitations in the performance of existing drilling tools. Our proposed instrument design has exceptional stiffness, stability, and accuracy as compared to other similar designs in the field. Initial prototypes were built and integrated with the state-of-the-art surgical robotic platform, da Vinci Research Kit (dVRK) for basic functional evaluation. Preliminary simulation and experimental study were performed and demonstrated the capability of the proposed

device for drilling and debridement. It is our hope that this novel tool will become a new benchmark tool for orthopaedic applications in terms of safety, precision, and dexterity.

1. OBJECTIVES AND SIGNIFICANCE

Robotic-assisted drilling has received considerable attention from researchers due to their advantageous features over conventional non-robotic-assisted one, such as high precision and exact penetration control through tissues. Because their shafts are mostly rigid and straight, conventional robotic-assisted surgical drills lack dexterity at distal end. As a result, those drills are limited in use in confined areas during MIS.

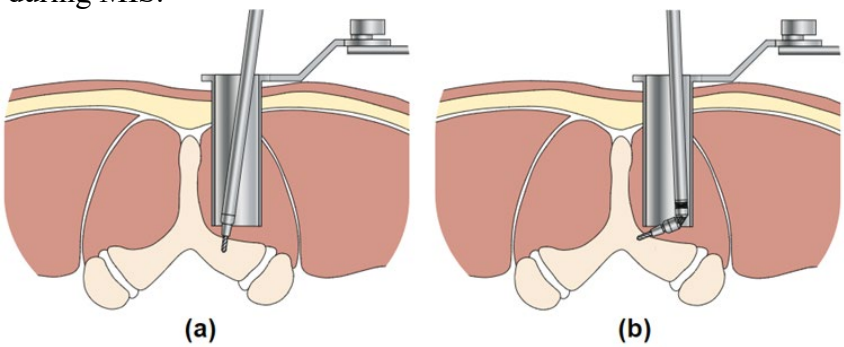

Figure 12 Conceptual view of drills in minimally invasive spine surgery. (a)Conventional straight-shaft drill; (b) articulated steerable drill.

To tackle the aforementioned problems, researchers have developed robotic-assisted steerable drills, which can achieve higher dexterity in confined spaces. Their proposed instrument designs, however, failed to offer high stiffness and dexterity due to the use of flexible continuum transmission, which limits their application in precise drilling in confined spaces.

The goal of this work is, therefore, to develop a robotic surgical drill with both high stiffness and dexterity. To this end, we use rigid articulated joints and non-flexible torque transmission, instead of flexible continuum manipulators and flexible shafts. One potential application of this drill is minimally invasive spine surgery, where surgeons access the spine through a slender tubular retractor. In this procedure, conventional drills lack dexterity at distal end due to their unsteerable nature (see Fig. 1 (a)). The proposed drill, on the contrary, enables surgeons to access target sites along different directions (see Fig. 1 (b)).

The main contribution of this project lies in the following aspects:

- Design and kinematics model of a tendon-driven articulated surgical drill. The proposed drill design offers high stiffness and dexterity simultaneously in drilling.
- Proposal of a modular tendon-driven articulated joint for drilling, consisting of a rolling joint capable of bending ±90° with high strength and a large lumen and an inner drilling torque transmission mechanism (universal joint or semi-spherical bevel gears). This joint, in combination with the inner torque transmission, allows for an abrupt bend in tight space (±45° for universal joint and ±90° for semi-spherical bevel gears), and, thanks to its modularity, it can be connected sequentially to gain higher DoFs.
- Integration of the developed drill to the dVRK as an exchangeable instrument. This provides a means to validate the drill as well as to assess the feasibility of teleoperated surgical drilling with a steerable drill.

2. RESEARCH METHODOLOGY

2.1. Mechanical Design

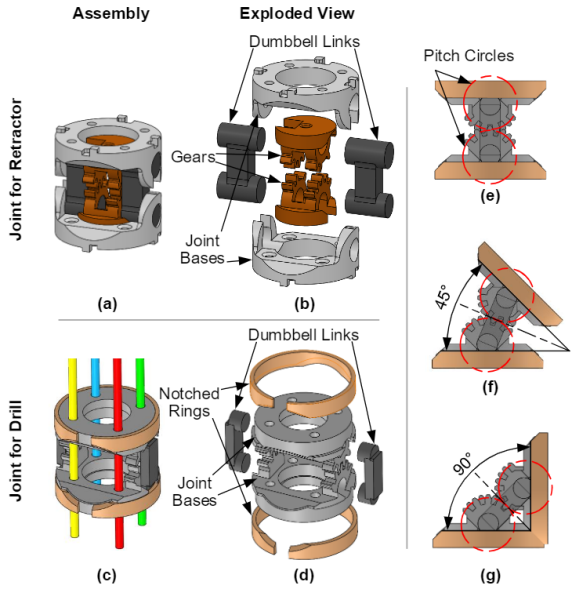

Figure 13 Design of a tendon-driven rolling joint with an inner lumen. (a)Joint assembly for the retractor ; (b) exploded view of (a); (c)assembly of the proposed joint for a drill; (d) exploded view of (c); (e)-(g) side views of the proposed joint at different joint angle.

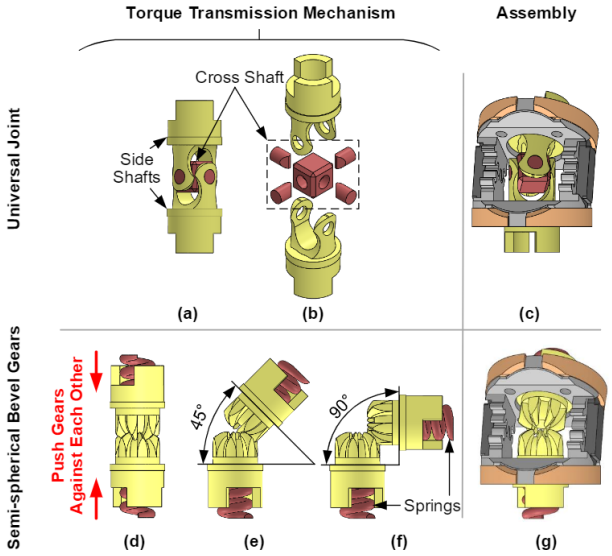

Figure 14 Torque transmission mechanisms. (a) Universal joint assembly; (b)exploded view of (a); (c) joint assembly with a universal joint (θ=30°);(d)-(f) semi-spherical bevel gears when joint angle θ=0°, 45°, and 90°,respectively; (g) joint assembly with semi-spherical bevel gears.

The key contribution of the drill design lies in its tip that works at the distal end in confined space, which consists of a drill bit and its collect and a 2-DoF articulated drilling wrist.

We adopt a rolling joint design from our previous work of a 8-mm robotic-assisted organ retractor, which is capable of rotating ±90° (see Fig. 2 (e)-(g)) and composed of two pairs of gears rolling against each other and one pair of dumbbell-shape links connecting the centers of the gears, as shown in Fig. 2 (a) and (b). In this joint, the two dumbbell links, which are large and wide along their shaft axes, are used to support axial and torsional forces as well as prevent lateral motion along dumbbell link shaft axes while the two pairs of gears located at the center of the joint to ensure rolling motion between the two joint bases. By relocating the gears and dumbbell links on this existing joint, we come up with a new 6.5-mm joint design with a 2.5-mm inner lumen to contain an inner torque transmission mechanism (see Fig. 2 (c) and (d)), which is suitable for drill applications. Compared to the joint from the retractor, the new design pushes the gears to the two sides of the joint, leaving enough space for drilling torque transmission and tendons at the center.

A universal joint (see Fig. 3 (a)) is used inside each rolling joint to transmit torque for drilling. It consists of an input shaft, an output shaft, and a cross shaft connecting the input and output shafts. The cross shaft is made of one cube with two through holes and four small shafts, which connect each other via interference fit and glue bond, as shown in its exploded view in Fig. 3 (b). Contrary to the flexible shafts used in existing works, which have minimum bending radii, a universal joint allows for a sharp bend (In our case, no problem has been found when the joint angle is within ±45° For illustration, a complete joint assembly with a universal joint inside is shown in Fig. 3 (c).

We also use a pair of semi-spherical bevel gears as the other torque transmission approach for the drill (see Fig. 3 (d)-(g)). Different from conventional bevel gears, whose pitch angles are fixed, semi-spherical bevel gears allow for varied pitch angles for rotation transmission.

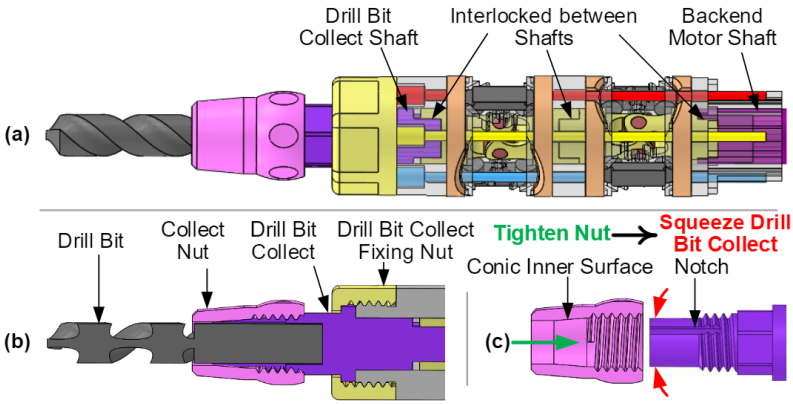

Figure 15 Drill tip assembly. (a) Torque transmission between shafts; (b) Cross section view of drill bit and its holder; (c) drill bit holding principle.

By combining two of the proposed drilling joints with their rotational axes perpendicular to each other, we obtain a 2-DoF articulated drilling wrist, as shown in Fig. 4 (a). Interlocking mechanical features are used on each pair of connected shafts to transmit torque from the proximal backend motor shaft all the way to the distal drill bit collect. To achieve higher dexterity, we can combine more of those joints.

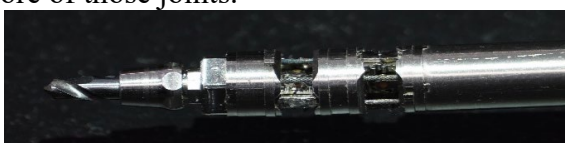

Figure 16 Drill tip

Figure 17 Drill instrument for the dVRK

Finally, the drill design was machined using a CNC machine as shown in Fig. 5. The drill tip was integrated with the dVRK as an exchangeable instrument for performance evaluation and experiments (see Fig. 6). The whole system setup is shown in Fig. 7.

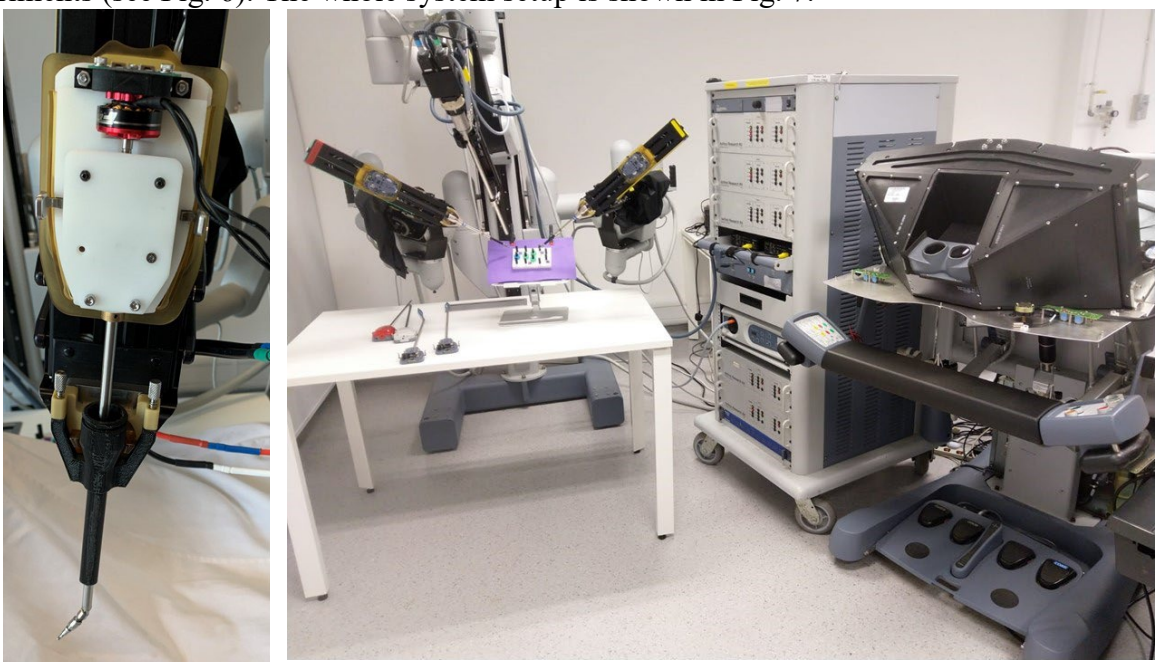

Figure 18 Proposed drilling instrument integrated with the dVRK.

2.2. Kinematics and Control

2.2.1. Kinematics

We first derive the kinematics from motor space to joint space (motor-tendon-joint kinematics) for the tendon-driven articulated wrist (the last two joints). It is worth noting that the 1st and 2nd joints of the wrist are corresponding to Joint 5 and 6 in Fig. 8, respectively. Since the first four joints have no difference from the original dVRK, which can be found in detail in the user guide of the dVRK. Next, we model the kinematics from joint space to task space (joint-task kinematics), based on the modified Denavit–Hartenberg (DH) convention.

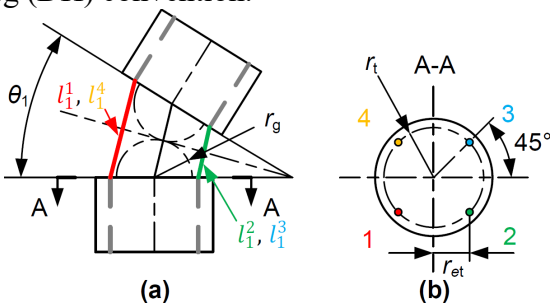

Figure 19 (a) Geometry of Joint 1 of the drilling wrist; (b) Cross-section view for tendon location.

Fig. 8 shows the geometry of Joint 1 of the drilling wrist and tendon locations. Based on the geometric relation, the mapping between motor space $\boldsymbol{\theta}_{\mathrm{m}}$ and joint space $\boldsymbol{\theta}$ can be represented as

$$\boldsymbol{\theta}_m = \frac{2r_{et}}{r_c}\begin{bmatrix} \sin\frac{\theta_1}{2} + \sin\frac{\theta_2}{2} \\ -\sin\frac{\theta_1}{2} + \sin\frac{\theta_2}{2} \end{bmatrix}$$

where $r_{et} = 2.5$ mm is the effective moment arm of the tendons and $r_c = 2.75$ mm is the radius of the capstan on the motor side.

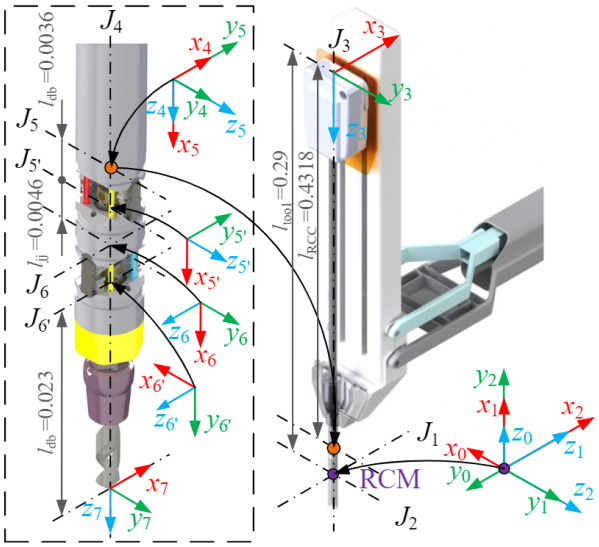

Figure 20 Frame definition of the proposed drilling system (unit: meter).

Frames are defined on the drilling system based on the modified DH convention (see Fig. 9). The first four joints (outer yaw, outer pitch, insertion, and rotation around insertion axis) are the same as the original dVRK joints, which are described in detail in the user guide of the dVRK. The last two revolute joints (rolling joints) are, however, different from the ones on the dVRK (hinge joints), as each rolling joint involves two consecutive rotations. Hence, two sub-joints are considered for each rolling joint, each of which rotates half of the whole joint angle (e.g., each of J5 and J5' rotates $q_5/2$). Finally, the last frame is defined on the tip of the drill bit.

2.2.2. Control Scheme

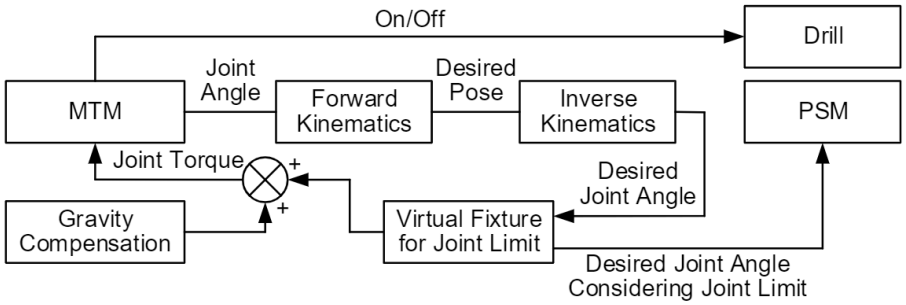

Figure 21 Control scheme of the proposed drilling system.

As shown in Fig. 10, the whole system utilizes a tele-operated control scheme. The desired pose of the drill bit is obtained from the forward kinematics of the MTM, which is then used to generate the desired joint angles on the PSM through numerical inverse kinematics. A virtual fixture framework is used to constrain the pitch and yaw instrument joints within a ±45° cone. Moreover, gravity compensation is used to remove the biased gravitational force to prevent users from muscle fatigue.

2.3. Experiments

Drill experiment was conducted with the developed drilling system on a piece of pig bone (see Fig.11). The results validate the developed drill in drilling bones.

Figure 22 drill experiment on a pig bone

3. RESULTS ACHIEVED

Please state the project achievement in this part and (if any) please state the patent application and/or product **commercialization plan**.

K. W. Samuel Au, et al., “Systems and methods for organ retraction and space opening,” US Provisional Patent, US 62/832,097.
K. W. Samuel Au, et al., “Systems and methods for articulated drilling,” In preparation for the US Provisional Patent

Product commercialization plan:

We have multiple plans for the commercialization in the future: (1) license/partner with local HK companies to co-develop the product together (2) Spin off a company and set up a joint venture with other local manufacturers to develop this product (3) explore other licensing and partnership opportunities overseas like Verb Surgical, inc (USA), Auris Surgical Robotics, inc (USA), Intuitive Surgical, inc (USA), MicroPort Shanghai (China), RoboMedical (China), United Imaging, inc (China), Mindray, inc (China).

When commercializing the technology, we will seek the help from the Knowledge Transfer Office and the Centre of Technology and Innovation of The Chinese University of Hong Kong.

4. PUBLICATION AND AWARDS

J[1] X. Chu, H. W. Yip, Y. Cai, T. Y. Chung, S. Moran and K. W. S. Au, "A Compliant Robotic Instrument With Coupled Tendon Driven Articulated Wrist Control for Organ Retraction," in *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 4225-4232, Oct. 2018.

J[2] H. Lin, C. Vincent Hui, Y. Wang, A. Deguet, P. Kazanzides and K. W. S. Au, "A Reliable Gravity Compensation Control Strategy for dVRK Robotic Arms With Nonlinear Disturbance Forces," in *IEEE Robotics and Automation Letters*, vol. 4, no. 4, pp. 3892-3899, Oct. 2019.

COMPLETED

DEVELOPMENT OF AN INERTIAL MICROFLUIDICS BASED APPROACH FOR THE ISOLATION OF MITOCHONDRIA FROM BIOLOGICAL SAMPLES

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[(3)]Graduate Institute of Biomedical Electronics and Bioinformatics, National Taiwan University, Taiwan

Project Start Date: 1 July 2017
Completion Date: 31 July 2019

INNOVATION AND PRACTICAL SIGNIFICANCE:

Defective mitochondria have been linked to several important human diseases, that urgently calls for the fundamental understanding of the disease mechanisms. To this end, presented here is a previously unavailable strategy enabling a fast and cheap isolation of mitochondria from samples of clinically relevant sizes. The proposed technology is revolutionary, yet highly transformable to a commercial product for routine clinical investigations and biological studies. Therefore, the developed platform will have a broad appeal to the pharmaceutical and clinical sectors targeting mitochondrial diseases. Table 1 summarizes the practical cost and expected performance for the isolation of mitochondria using the inertial based approach compared with other commercially available kits.

Table 1. Comparison between the Inertial Based Isolation of Mitochondria and the Commercially Available Kits.

	Inertial Based	Thermofisher	Abcam	Qiagen
Assay Time (Post-Lysis)	10 min	40 min	>30 min	>45 min
Required Cells	100	2×10^7	4×10^7	5×10^6
Bench Top Availability	Yes	Yes	Yes	Yes
Purity	High	High	High	High
Required Reagent Exchange	No	Yes	Yes	Yes
Price Per Isolation (HKD)	20	45	97	296

ABSTRACT
This project aims to develop a novel approach for rapid isolation of mitochondria from samples of clinically relevant sizes. While currently available methods are mostly laborious and not suitable for small-scale analyses in the clinics, the proposed approach is able to handle 200 microliters of sample and process the isolation within 30 minutes. Aside from the possibility for small-scale analysis, the proposed approach offers many distinct features, including the simple procedures, undemanding equipment request, minimal damages to the isolated mitochondria, and continuous batch processing. Possibilities to analyse mitochondria from a limited amount of clinically relevant patient samples are expected to expand our knowledge towards the basic biological mechanisms of mitochondrial function, and to elucidate how mitochondria are involved in the development of diseases such as cancers, premature aging syndromes, diabetes and neurodegenerative disorders. For instance, it becomes practical to obtain mitochondria from the patient samples, and to elucidate how defective mitochondria link to the mitochondria-associated diseases. Furthermore, the isolation principle may be tailored for an array of subcellular fractions, rendering efficient identifications and characterizations of intracellular organelles of interest and advancing the study of biology and medicine continuously.

1. OBJECTIVES AND SIGNIFICANCE

1.1. Objectives

- To optimize and fabricate the inertial microfluidic chip for the isolation of mitochondria
- To demonstrate effective recovery of mitochondria using purified mitochondria as a model
- To develop a series of protocols for the characterization of isolated mitochondria
- To revise the design chip for a rapid isolation of functional mitochondria from crude human cell lysates of a clinically relevant sample size

1.2. Significance

Defective mitochondria have been linked to several important human diseases, that urgently calls for the fundamental understanding of the disease mechanisms. To this end, presented here is a previously unavailable strategy enabling a fast and cheap isolation of mitochondria from samples of clinically relevant sizes. The proposed technology is revolutionary, yet highly transformable to a commercial product for routine clinical investigations and biological studies. Therefore, the developed platform will have a broad appeal to the pharmaceutical and clinical sectors targeting mitochondrial diseases. *Table 1 summarizes the practical cost and expected performance for the isolation of mitochondria using the inertial based approach compared with other commercially available kits.*

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Purity	High	High	High	High
Required Reagent Exchange	No	Yes	Yes	Yes
Price Per Isolation (HKD)	20	45	97	296

2. RESEARCH METHODOLOGY

2.1. Task 1: Optimization of the Microfluidic Chip Using Purified Mitochondria

We have designed and fabricated the chip capable of separating polystyrene particles of 1.9 μm and 7.32 μm (**Figure 1a**). The inertial lift and so-called Dean drag forces collectively render particles of different sizes to migrate differently along the channel width. More specifically, mitochondria of

smaller sizes compared to other cytosolic fractions (i.e. nuclei and cell debris) migrate to the outer half of the channel, whereas the larger cellular organelles move to the inner half of the channel. The size-dependent equilibrium position is determined by the inertial forces of the particulates and the Dean vortices generated by the spiral channel geometry. Prior to the start of this project, we have optimized that the design to direct up to 90% of mouse liver mitochondria into the targeted outlet. Due to the heterogeneous nature of mitochondria, the microfluidics design (channel geometry) and the operating flow rates have been optimized empirically with purified mitochondria as shown in **Figure 1b**.

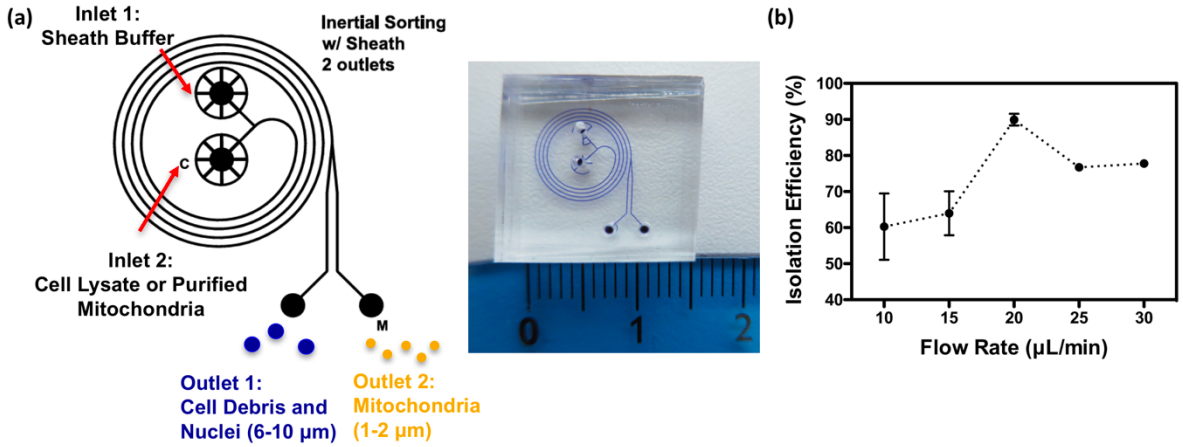


Figure 1. (a) Schematic showing the design of the chip. (b) Optimization of flow rates using purified mitochondria.

2.2. Task 2: Characterization of the Isolation Performance

As a parallel effort of Task 1, we have established relevant characterization techniques to evaluate (1) the isolation efficiency, (2) the isolation purity and (3) the mitochondrial functionality.

(1) The isolation efficiency: As a fast method to quantify the amount of retrieved functional mitochondria isolated by the microfluidic chip, the active mitochondria are stained with a commercially available fluorescent dye, MitoTracker™ Red FM. This red-fluorescent dye accumulates in mitochondria with a membrane potential - a hallmark for functional mitochondria. We have established the protocols by measuring the total fluorescence intensity (ex. by a fluorimeter).

(2) Isolation purity: Western blotting analysis will be performed to check the purity of the isolated mitochondria. The Ku86 protein will be used as the marker for the nuclei, while Tom20 will be used to identify the mitochondrial specific protein. The isolation purity will be determined by comparing the fractions of the two proteins from samples retrieved from the two outlets.

(3) The mitochondrial functionality: To further validate whether the retrieved mitochondria retain their biological functionality, mitochondrial generated reactive oxygen species (ROS) from unsorted and sorted mitochondria will be measured by a fluorescently labelled probe 2',7'-dihydrodichlorofluorescein (DCFH) which emits an intense green fluorescence upon deacylation and subsequent oxidation. ROS, as a typical product of cellular metabolism, are mainly generated by mitochondria. Therefore, the measured fluorescence intensity of DCFH may serve as an indication of the mitochondrial functionality after isolation.

2.3. Task 3: Optimization of the Chip Design for Crude Biological Samples

Due to its large diversity, isolation of mitochondria presents a tangible challenge when it comes to separating this organelle from other cellular components. The subsequent task is to optimize and

validate the chip design for handling biological crude sample. Human embryonic kidney cells (HEK293) are used as a model cell line. Crude cell lysate will be prepared following standard protocols. Briefly, the cells will be homogenized by lysing the cell membranes in a hypotonic buffer followed by mechanical disruption with a Dounce glass homogenizer. Samples from the two individual outlets are collected without further post-processing and then analysed by the characterization techniques developed in Task 2.

3. RESULTS ACHIEVED

3.1. Isolation of mitochondria from crude biological samples

Through pre-processing, namely cell lysis by Dounce homogenization, current chip design can isolate 75% of functional mitochondria with 200 µL of crude cell lysates in 20 minutes (**Figure 2a**). As observed in **Figure 2b**, the isolation efficiency decreases as the cell concentration increases. This is not surprising because the excessive cellular contents may affect the flow profile, rendering less optimal sorting. An optimized protocol has been set up to allow the isolation of mitochondria from cell lysates of 10 million cells/mL.

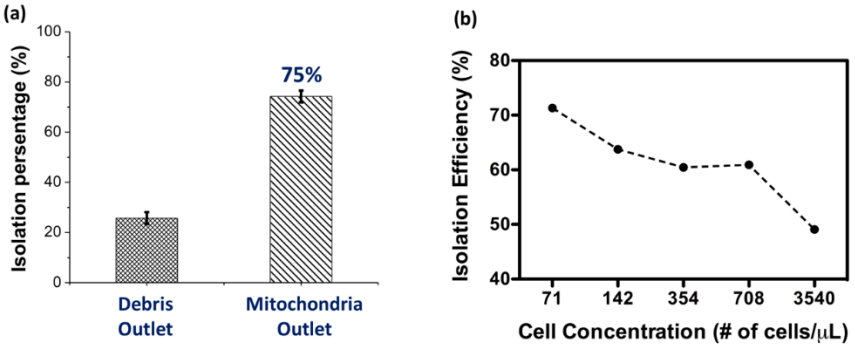


Figure 2. (a) Mitochondrial isolation efficiency of the current design. (b) Negative correlation of the cell concentration and isolation efficiency.

3.2. Isolating subpopulations of mitochondria

Mitochondria undergo fusion and fission processes for the quality control upon cellular exposure to stress. We hypothesize that the changes in morphology and mass of mitochondria may serve as an indication of the status of cells. We have therefore proceeded to revise the chip design (**Figure 3a**) for the isolation of mitochondrial subpopulations presumably by their mass. Crude sample samples were pre-processed based on previously optimized protocol. Previously established characterization techniques, including the isolation efficiency, purity and mitochondrial functionalities, were employed to study the isolated mitochondria. Gene-modified cell lines were used to optimize the operating volume flow at 20 µL/min per the intended outlet of collection (i.e. the heavier entities at the inner ring whereas the lighter entities migrate towards the outer ring. Preliminary results have suggested the subpopulation collected from the outer outlet exhibits a larger geometric size compared to the counterparts collected from the inner outlet (**Figure 3b**) as quantified by the forward scattering signal from flow cytometric analysis. However, the MitoTracker signal, as a measure of membrane potential, does not show significant changes before or after isolation, or among different outlet (**Figure 3c**). On the bright side, the proposed isolation process appears quite gentle to the mitochondria, thus the intactness of mitochondria may be maintained, also as witness by the observations under transmission electron microscopy (**Figure 3d**). Interestingly, different activities have been observed from mitochondria isolated from different outlet. To validate the biological functionality of retrieved mitochondria, the apurinic/apyrimidinic endonuclease 1 (APE1) activity of sorted mitochondria was measured. APE1 is an essential DNA repair enzyme involved in the maintenance of mitochondrial DNA stability and thereby maintenance of mitochondrial function. The measured APE1 activity was normalized to the total amount of protein for a fair assessment indicated as the repair activity per unit of mitochondria. Results from **Figure 3e** showed the repair

activity of mitochondria from the middle outlet was higher than that of other two outlets, implying that the functionality of mitochondria may be related to their physical properties.

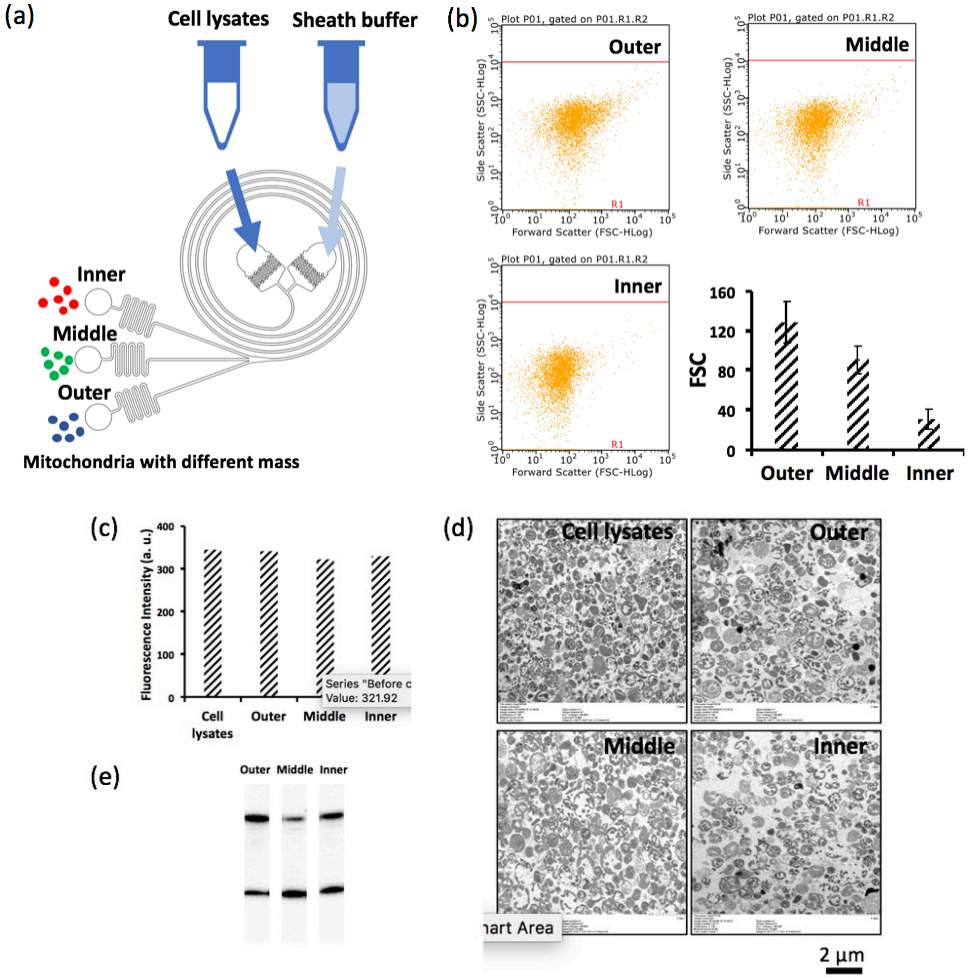


Figure 3. (a) Overview of the chip. (b) Scatter plot of mitochondria subpopulations analysed by flow cytometer. Intactness of mitochondria validated by (c) mitotracker staining and (d) TEM. (e) Mitochondrial functionalities measured by DNA repair assay.

3.3. Pre-processing of cells

Dounce homogenization has been the most widely used method for breaking up the cell membrane, however, the level of shear is largely determined by the clearance between the pestle and the mortar, as well as the number of strokes and grinding speed. The poor reproducibility due to the operational variation poses a significant challenge for the continuous optimization of our device's isolation efficiency. To fundamentally resolve the limitation, we have moved forward and designed a "microscale cell shredder" that generate cell lysis on chip as to pre-processing of cells for on-chip mitochondria extraction. The proposed microfluidic system consists of a cross-junction microchannel where cell suspension and lysis buffer were introduced at a cross-junction zone from opposite direction (**Figure 4a**). The mean shear stress was modulated around 16.4 Pa by controlling the volumetric flow rate at 60ul/min, which has been previously proven effective for cell lysis at the macro scale. To validate the cell disruption capability from small sample volume and low cell concentration, cell suspension of 200 μL (1×10^5 cells/mL) were shredded on-chip and the lysis efficiency was compared with the standard Dounce Homogenizer. As shown in **Figure 4b**, hydrodynamic shear resulted in higher lysis efficiency (~ 85%) compared to the Dounce Homogenizer (~ 70%) for both HEK293 and C2C12 cells of similar membrane stiffness.

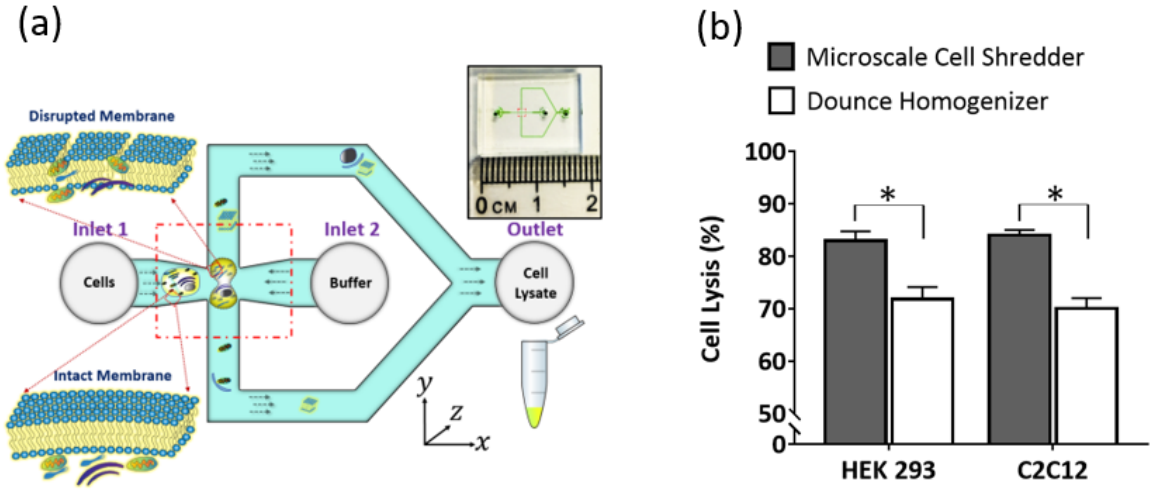


Figure 4: (a) Schematic illustrations of the concept of cell lysis using hydrodynamic shear stress. (b) Comparison of cell lysis efficiency between the on-chip shearing and the Dounce Homogenizer. Results were plotted as mean ± S.D. (n = 3 independent experiments, *P <0.05).

As a logical step forward, we plan to integrate both the extraction and isolation modules on-chip as an all-in-one processing strategy for mitochondrial extraction. Furthermore, similar strategy is also expected to adopt for the isolation of other subcellular organelles, such as autophagosomes.

3.4. Project achievement and product commercialization plan

Preliminary data obtained under the support of this project has served as the foundation of the following submitted grant proposals:

- External competitive: RGC General Research Fund (GRF): "On-Chip Extraction and Isolation of Mitochondria and the Subsequent Characterization of Mitochondrial Subtypes" (Ref. no.: 14201518), PI: Megan Yi-Ping Ho (Not Funded)
- External competitive: Columbus Program, Ministry of Science and Technology (MOST), Taiwan: "Integrative Platform of Mitochondrial Toxicity Screening" (Ref. no.: 107WFA0110185), PI: An-Chi Wei, Co-I: Megan Yi-Ping Ho (Funded)
- Internal competitive: Research Committee Funding for Research Sustainability of Major RGC Funding Schemes, Deploying Next-generation Quality Assessment and Treatment for Assisted Reproductive Technology in the Guangdong-Hong Kong-Macao Greater Bay Area (MD18764), PI: Prof. Tin-Lap Lee, Co-PI: Megan Yi-Ping Ho (Funded)
- External competitive: RGC Research Impact Fund (RGC), Improving assisted reproductive technology service and outcome by translating genomic discoveries of oocyte aging into next-generation early assessment and treatment (R4033-19), PI: Prof. Tin-Lap Lee, Co-PI: Megan Yi-Ping Ho (Under Review)
- External competitive: RGC Collaborative Research Fund, Development of novel oocyte quality screening methods and autologous stem cell transfer treatment for IVF women of advanced age (C4036-19G), PI: Prof. Tin-Lap Lee, Co-PI: Megan Yi-Ping Ho (Renewal under Review)

Commercialization Plan

Together with Prof. Tin-Lap Lee (SBS), we have started up a company (EggLogics) based on a provision patent entitled “A Method to Improve Oocyte Quality through Autologous Mitochondrial Transfer from Adult Stem Cells” (USPTO, Application no. 62714646). The company is currently preparing an application to enter the IncuBio Program in the HK Science and Technology Park.

4. PUBLICATION AND AWARDS

The results obtained from this project have resulted in the following published articles.

C[1] C. Chang, Y. P. Ho and A. C. Wei, "Mathematical Modeling of Mitochondrial Quality Control in Mitochondrial Life Cycle and its Role in Ageing," *Single-Cell Biophysics: Measurement, Modulation, and Modeling, Biophysical Society Thematic Meeting*, Taipei, Taiwan, 2017.
C[2] C. Chang, Y. P. Ho and A. C. Wei, "Computational Modeling of Mitochondrial Metabolism and Dynamics in Ageing," *The 1st International Mitochondria Meeting for Young Scientists*, Kyoto, Japan, 2018.
C[3] Q. Xiao, M. H. Rahman, S. Zhao and Y. P. Ho*, "Continuous Deformation of Cell Membrane On-Chip for Effective Cell Lysis," *22th International Conference on Miniaturized Systems for Chemistry and Life Sciences (MicroTAS)*, Kaohsiung, Taiwan, 2018.
C[4] M. H. Rahman, S. Zhao Q. Xiao, C. Tesauro, F. Qu, T. Stevnsner, A. C. Wei, and Y. P. Ho*, "Extraction and Isolation of Mitochondria from Biological Samples via Microfluidics," *14th Annual IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, Bangkok, Thailand, 2019.
C[5] C. Chang, Y. Ye, Q. Xiao, Y. P. Ho, A. C. Wei, "In silico simulation of metabolic regulation on mitochondrial dynamics in ageing," *9th WACBE World Congress in Bioengineering*, Taipei, Taiwan, 2019.
J[1] M. H. Rahman, Q. Xiao, S. Zhao, F. Qu, C. Chang, and A. C. Wei, Y. P. Ho*, "Demarcating the Membrane Damage for the Extraction of Functional Mitochondria," *Microsystems & Nanoengineering*, 4 (1), 39, 2018.

There are a few manuscripts under preparation, which are not included on the list.

Award:

Mr. Chen Chang has been awarded a Young Investigator Scholarships by the YoungMito Program: http://www.fbs.osaka-u.ac.jp/YoungMito2018/YoungMito2018/Scholarships_%26_Awards.html

Multimedia Technologies & AI Track

Research Reports
In Multimedia Technologies and AI

Newly Funded Projects (2020-2022)	* Improving Workflow Recognition of Robot-assisted Surgery via Exploration into Future Scenes for Surgical Video Analysis
Continuing Projects (2019-2021)	* Deep Learning Based Audio-visual Recognition of Cantonese Disordered Speech
Completed Project (2017 - 2019)	* Achieving Simultaneous Spectral-Spatial Super-Resolution via Reconstruction from Multispectral and Hyperspectral Images

The following reports are enclosed in "Research Highlights" printed in August 2017

Completed Project (2014 - 2016)	* Managing and Analyzing Big Graph Data

The following reports are enclosed in "Research Highlights" printed in June 2015

Completed Project	
(2012)	* Face Recognition Across Ages Through Binary Tree Learning

The following reports are enclosed in "Research Highlights" printed in June 2014

Completed Projects	
(2011)	* Semantic Analysis for Image Resizing * Time Critical Applications over a Shared Network * Amplify-and-forward Schemes for Wireless Communications

The following reports are enclosed in "Research Highlights" printed in 2013

Completed Projects	
(2010)	* FADE: Secure Cloud Storage with File Assured Deletion * Security and Detection Protocols for P2P-Live Streaming Systems
(2009)	* An Opportunistic Approach to Capacity Enhancement in Wireless Multimedia Networks * Computer-Aided Second Language Learning through Speech-based Human-Computer Interaction

The following reports are enclosed in "General Report and Research Highlights 2009-2011" printed in October 2011.

Completed Projects	
(2008)	* Pattern Computation for Compression and Performance Garment
(2007)	* Real-time Transmission of High Definition (HD) 3D Video and HD Audio in Gigabit-LAN * High Dynamic Range Image Compression and Display * Multimedia Content Distribution over Hybrid Satellite-Terrestrial Communication Networks
(2006)	* Automatic Video Segmentation and Tracking for Real Time Multimedia Services * Information Retrieval from Mixed-Language Spoken Documents * Wireless Networks and Its Potential for Multimedia Applications

The following reports are enclosed in "Research Highlights 2005-2007" printed in January 2008.

Completed Projects	
(2005)	* Mobile Wireless Multimedia Communication * An Automatic Multi-layer Video Content Classification Framework * Automatic Multimedia Fission, Categorization and Fusion for Personalized Visualization in Multimedia Information Retrieval

(Funded Year)

IMPROVING WORKFLOW RECOGNITION OF ROBOT-ASSISTED SURGERY VIA EXPLORATION INTO FUTURE SCENES FOR SURGICAL VIDEO ANALYSIS

Principal Investigator: Professor Qi DOU
Department of Systems Engineering and Engineering Management, CUHK

Project Start Date: 1 August 2020

ABSTRACT

Artificial intelligence for promoting surgical context-awareness based on endoscopic video analysis serves as a core fuel for reliable cognitive assistance in the next generation of robot-assisted surgery. Towards this mission, automated workflow recognition, i.e., being aware of current state of the surgical procedure being performed, is the fundamental problem, which is the prerequisite for almost any form of intelligent assistance for automated surgery. Existing methods have formulated this problem into frame-wise or video clip-wise classification tasks, and adopted computer vision approaches with supervised learning. However, they are limited to only analyzing previous frames to current state, without exploring ahead to future frames, which is far from how humans make decisions. This project aims to overcome the limitation and hence improving workflow recognition accuracy, by innovating a reinforcement learning system with tree search for future exploration, alongside with pixel-wise future scene synthesis technologies for enabling online prediction mode and complex stochasticity consideration. To our knowledge, this is the first attempt to systematically study how to incorporate the crucial future information for robot-assisted surgery context-awareness. The outcomes will not only advance methodology and knowledge on deep learning and surgical robotics perception, but also promote AI technique transfer to the highly challenging yet impactful interdisciplinary area of medical interventions.

INNOVATION AND PRACTICAL SIGNIFICANCE:

In this project, we will address the problem of surgical workflow recognition for endoscopic video analysis, which serves as the fundamental role for enhancing context-awareness in robot-assisted surgery. As mentioned, existing approaches only make predictions based on previous video frames of the current state. Such blindness to future information consideration would lead to insufficient contextual clues, inconsistent segment-level smoothness, unreliable prediction at complex scenes, and suboptimal understanding of the on-going surgical activity. This project will address the above limitations with novel learning methods proposed from three hierarchical aspects: (1) we will first establish a reinforcement learning framework with a tree search algorithm, which is fundamentally novel from existing supervised convolutional networks based frameworks, in order to allow the future frames being explored through the value network. (2) we will innovate a video prediction approach for synthesizing future frames for the important use of online mode when there is be no future frame available in real-time. (3) we will incorporate the stochasticity for longer-term future scene predictions, which will be able to take into account future uncertainty in human-like manner

for abnormality alert and risk assessment. In the last, we will demonstrate the practical significance of the proposed techniques on two robotics surgery scenarios: i.e., da Vinci robot-assisted suturing which is the most common process, and the cholecystectomy procedure which is more complex. It is promising that the surgical workflow recognition with human-like decision intelligence will ultimately facilitate surgeon performance, improve intervention outcome and benefit patient care.

PROJECT OBJECTIVES:

•We aim to innovate a breakthrough surgical workflow recognition framework by taking advantage of tree search associated with an AlphaGo-based sequential decision process, in order to overcome current limitations of lack of future information modeling and local optimum in deep learning methods, towards enabling the AI system to make decisions in a way more closer to how the surgeons think in clinical practice.

•We will extend our reinforcement learning framework to enable online mode prediction, in which the workflow recognition can be conducted in real-time surgery, by innovating methods for deterministic video frames prediction to forecast future scenes when such information is unavailable, which is unexplored so far.

•We are going to further explore various possibilities and uncertainties of future evolution by incorporating stochasticity into future frame predictions especially for a longer-term future forecasting, which is valuable and important for inter-operative abnormality alert and risk management in practice.

•Finally, our downstream demonstrative application scenarios include the da Vinci robot-assisted suturing which is the most common surgical process and the cholecystectomy procedure which is a more complicated surgical workflow. We already have datasets for both applications and conducted relevant perception analysis based on these videos.

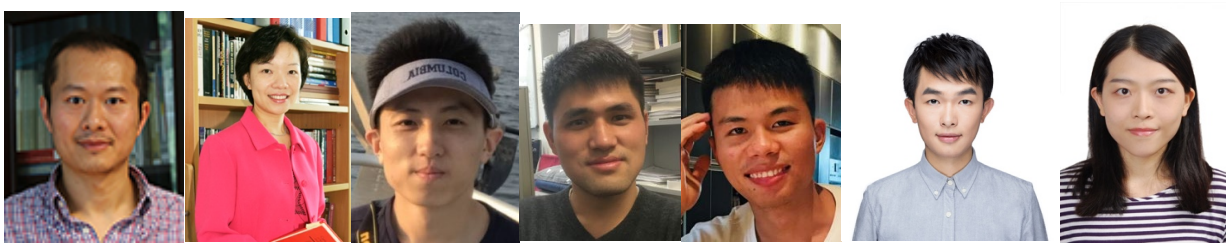
WORK IN PROGRESS

DEEP LEARNING BASED AUDIO-VISUAL RECOGNITION OF CANTONESE DISORDERED SPEECH

Principal Investigator: Professor Xunying LIU
Department of Systems Engineering and Engineering Management, CUHK

Co-Investigator: Prof. Helen Mei-Ling MENG [1]

[1] Dept. of Systems Engineering and Engineering Management, CUHK



Reporting Period: 1 August 2019 – 30 April 2020

INNOVATION AND PRACTICAL SIGNIFICANCE:

To include a paragraph to highlight specifically the innovation and practical significance of your work. Both VC and the door would like to see more research endeavors be directed to innovation and technology transfer for the betterment of mankind.

Automatic speech recognition (ASR) for disordered speech is a challenging task. Speech disorders such as dysarthria lead to severe degradation of speech quality, highly variable voice characteristics and large mismatch against normal speech. State-of-the-art speech recognition systems designed for normal speech often produce poor recognition accuracy when applied to disordered speech. Human speech production is a bimodal process based on audio-visual representation. The visual information is invariant to acoustic signal corruption and can provide complementary information to the speech recognizer. This motivates the use of visual information to improve disordered speech recognition. However, among people with speech disorders, their underlying medical conditions such as Parkinson disease and co-occurring disabilities increase the difficulty to record high quality audio-visual data in large amounts that are necessary for audio-visual speech recognition (AVSR) system development. For example, in addition to the degradation of voice quality, head movements and different angles facing the camera are often found in recoding.

To the best of our knowledge, this project is the first attempt among the international multimedia, AI and speech technology research communities to use deep learning based AVSR approaches for disordered speech recognition. It is also the first one dedicated for Cantonese disordered speech. The outcome of this research will allow easier and more natural communication for Cantonese speaking people suffering from speech disorders with the outside world, improve their social inclusion and quality of life, and to support research and development efforts to create speech based assistive technology applications for such people. These can increase the cost effectiveness and quality of care and health service for them. This research will form a strong basis for future work on disordered speech recognition for Mandarin and other Chinese dialects to help a much larger number of similarly affected people in China.

ABSTRACT

Speech disorders such as dysarthria are commonly found among the elderly population which disrupt their verbal communication with the outside world. Speech disorders not only introduce a negative impact on their quality of life but also increase the cost of care. As Hong Kong is ageing rapidly, the number of people with speech disorders will further increase. Due to the large mismatch between normal and disordered speech, state-of-the-art speech recognition systems designed for normal speech often produce very low recognition accuracy when applied to disordered speech. Hence, there is a pressing need to develop new technologies for building disordered speech recognition systems of high accuracy performance. By capitalizing on our previous research which produced the best accuracy on disordered English speech recognition, and also motivating from the bimodal nature of human speech production, this project will develop novel deep learning based audio-visual speech recognition (AVSR) techniques for Cantonese disordered speech. Exemplar ASVR systems and recipes for publicly available Cantonese disordered speech corpora will be developed to provide insights for designing state-of-the-art AVSR systems on such data. The outcome of this project allows easier and more natural communication for Cantonese speaking people in Hong Kong and Great Bay Area who suffer from speech disorders with the outside world. This project will also form a strong basis for future research on disordered speech recognition for Mandarin and other Chinese dialects to help a much larger number of similarly affected people in China.

1. OBJECTIVES AND SIGNIFICANCE

1. Using visual information to improve dysarthric speech recognition performance
2. Deriving novel deep AVSR methods to robustly model limited amounts of audio-visual disordered speech data
3. Deriving fast AVSR model adaptation methods to handle speaker dependent impairment characteristics
4. Developing exemplar AVSR systems and recipes to provide insights for designing state-of-the-art dysarthric speech recognition systems
5. Allow easier and more natural speech based communication for people suffering from speech disorders with the outside world, improve their social inclusion and quality of life

2. RESEARCH METHODOLOGY

1) Development of baseline ASR and AVSR systems for Cantonese disordered speech

Baseline deep neural network based ASR and ASR systems will be constructed using CUDYS, the largest publicly available CUHK Cantonese disordered speech corpus. When developing these systems, state-of-the-art deep learning based ASR model architectures that have been successfully adopted in our CUHK English dysarthric speech recognition system will be used to build the baseline Cantonese ASR system for disordered speech. Deep neural network based Cantonese AVSR systems using a fusion of acoustic and visual features are constructed to serve as the baseline AVSR approach. In order to improve the recognition performance on disordered speech data, an additional large commercial Cantonese normal speech corpus (SpeechOcean, 205.8 hours from 500 healthy Cantonese speaking subjects) was incorporated and mixed with CUDYS (3.3 hours) to train our ASR and AVSR systems [3].

2) Data augmentation for audio-visual recognition of disordered speech

Audio-visual speech recognition (AVSR) technologies have been successfully applied to a wide range of tasks. When developing AVSR systems for disordered speech, the following challenges arise for data intensive state-of-the-art deep learning techniques. The underlying neuro-motor conditions of people with speech disorders, often compounded with co-occurring physical disabilities, lead to the difficulty in collecting large quantities of speech that are required for ASR and AVSR systems development. In order to address this data sparsity issue by leveraging large amounts of healthy speakers' speech data that are more widely available and easier to obtain, we developed novel data augmentation and cross-domain visual feature generation techniques.

First, a set of data augmentation techniques for disordered speech recognition, including vocal tract length perturbation (VTLP), tempo perturbation and speed perturbation were used. Both normal and

disordered speech were exploited in the data augmentation process [7]. Variability among impaired speakers in both the original and augmented data was modeled using learning hidden unit contributions (LHUC) based speaker adaptive training. Second, a cross-domain visual feature generation approach is proposed. Audio-visual inversion DNN systems constructed using widely available out-of-domain audio-visual data were used to generate visual features for disordered speakers for whom video data is either very limited or unavailable [8].

3) Bayesian Gated deep neural network AVSR systems for modelling limited disordered speech

A commonly used approach in state-of-the-art DNN based AVSR systems is to concatenate the acoustic and visual features at the input layer. This approach works well when the visual features being used are robust and contain sufficient discriminative information for classifying speech. However, in addition to the well-known degradation of voice quality, there are several new challenges when developing AVSR systems for people with speech disorders. First, their underlying medical conditions such as cerebral palsy and Parkinson disease combined with co-occurring disabilities increase the difficulty to record high quality visual data. For example, head movements and different angles facing the camera are often found. These make the accurate detection of lip regions very difficult, and the subsequent extracted visual features unreliable to use. Second, in common with the audio data, the diverse causes leading to speech disorders and the resulting symptoms create a large variability among individual impaired speakers.

In order to address these issues, we will use a novel Bayesian gated neural network (BGNN) [1] based AVSR architecture. This is realized by positioning an additional multiplicative gating layer between the input and first hidden layer. This layer's outputs are used to dynamically weight the contributions from visual features before they are further concatenated with acoustic features. This allows a more flexible fusion of acoustic and visual features that can learn to suppress non-discriminant visual data. Speaker dependent BGNN models are constructed to handle speaker level variability. In order to address the data sparsity issue, a posterior distribution over the gating layer weight and bias parameters is used to model their uncertainty given limited and variable data. Efficient variational inference will be also used in BGNN system training.

4) Exploiting pitch features for disordered Cantonese speech recognition

Pitch features have long been known to be useful for recognition of normal speech. However, for disordered speech, the significant degradation of voice quality renders the prosodic features, such as pitch, not always useful, particularly when the underlying conditions, for example, damages to the cerebellum, introduce a large effect on prosody control. Hence, both acoustic and prosodic information can be distorted. To the best of our knowledge, there has been very limited research on using pitch features for disordered speech recognition. In this paper, a comparative study of multiple approaches designed to incorporate pitch features is conducted to improve the performance of two disordered speech recognition tasks: English UASpeech, and Cantonese CUDYS. A novel gated neural network (GNN) based approach is used to improve acoustic and pitch feature integration over a conventional concatenation between the two. Bayesian estimation of GNNs is also investigated to further improve their robustness [2].

5) AVSR system adaptation to diverse speaker impairment characteristics

The highly diverse impairment characteristics at speaker level creates large variation in audio-visual disordered speech data. Speaker adaptation techniques play a key role in reducing the mismatch between AVSR systems and target users. Model based DNN adaptation techniques often require a significant amount of data to robustly learn speaker dependent adaptation parameters. For example, in the commonly used learning hidden unit contributions (LHUC) based DNN adaptation, speaker dependent high dimensional hidden layer output scaling vectors are used [7][8]. When limited adaptation data from individual impaired speakers are available, the standard LHUC method is prone to over-fitting and poor generalization. To address the issue, Bayesian learning of hidden unit contributions (BLHUC) will be investigated in our research. In contrast to current adaptation methods requiring large amounts of disordered speech data, this technique is expected to allow deep learning based AVSR systems to be rapidly adaptable to individual impaired speakers using very little data, for example, a few seconds of audio-visual disordered speech.

6) Neural architecture search for speech recognition

Deep neural networks (DNNs) based automatic speech recognition (ASR) systems are often designed using expert knowledge and empirical evaluation. In our latest research, a range of neural architecture search (NAS)

[5] techniques are used to automatically learn two hyper-parameters that heavily affect the performance and model complexity of state-of-the-art factored time delay neural network (TDNN-F) acoustic models: i) the left and right splicing context offsets; and ii) the dimensionality of the bottleneck linear projection at each hidden layer [6]. These include the standard differentiable architecture search (DARTS) method fully integrating the estimation of architecture weights and TDNN parameters in lattice-free MMI (LF- MMI) training; Gumbel-Softmax DARTS that reduces the con- fusion between candidate architectures; pipelined DARTS that circumvents the overfitting of architecture weights using validation data; and penalized DARTS that further incorporates resource constraints to adjust the trade-off between performance and system complexity. Parameter sharing among candidate architectures was also used to facilitate efficient search over up to 7^28 different TDNN systems.

3. RESULTS ACHIEVED SO FAR

The up to date project achievements and highlights from August 2019 to May 2020 are summarized as below.

1) Using speed perturbation based speech data augmentation, the final speaker adapted system constructed using the UASpeech corpus and the best augmentation approach based on speed perturbation produced up to 2.92% absolute (9.3% relative) word error rate (WER) reduction over the baseline system without data augmentation, and gave an overall WER of 26.37% (best known published results so far) on the test set containing 16 dysarthric speakers. The total amount of disordered speech data was increased by approximately 7 times from the original data collection [7].

2) Using the cross domain visual feature generation approach we developed, experiments conducted on the UASpeech corpus also suggest that the proposed cross-domain visual feature generation based AVSR system consistently outperformed the baseline ASR and AVSR systems constructed using the original visual features. An overall word error rate reduction of 3.6% absolute (14% relative) was obtained over the previously published best AVSR system on the 8 UASpeech dysarthric speakers with audio-visual data of the same task. The total amount of audio-visual disordered speech data was increased by approximately 9 times from the original audio-visual data collection on the same task [8].

3) Using the Bayesian gated neural network (BGNN) based AVSR systems we developed, experiments conducted on the UASpeech dysarthric speech corpus suggest the proposed BGNN AVSR system consistently outperforms state-of-the-art deep neural network (DNN) baseline ASR and AVSR systems by 4.5% and 4.7% absolute (14.9% and 15.5% relative) in word error rate [1].

4) we published the first work that incorporates pitch features for disordered speech recognition. Second, this paper presents the first attempt to leverage GNN and BGNN approaches for prosodic feature selection to improve the performance of disordered speech recognition and speech recognition systems in general. Experiments conducted on the two corpus, UASpeech and CUDYS, suggest that a selection mechanism is needed for a robust integration of acoustic and pitch features for disordered speech recognition tasks [2].

6) Using the neural architecture search techniques we proposed, experiments conducted on a 300-hour conversational telephone speech recognition task suggest the NAS auto-configured TDNN-F systems consistently outperform the baseline LF-MMI trained TDNN-F systems using manual expert configurations. Absolute word error rate reductions up to 1.0% and relative model size reduction of 29% were obtained [6].

To summarize, in support of addressing questions raised by the panel members during the March 2019 presentation regarding data scarcity and system performance analysis over different forms of speech disorder and severity levels, we have developed novel techniques to augment and expand the limited disordered audio-visual speech data by up to a factor of 9 times to over two hundred hours in the first 8 months of this project. The large variability among impaired speakers in both the original audio and augmented data was effectively handled by powerful speaker adaptation techniques. State of the art speech recognition accuracy performance results were obtained on the largest publicly available disordered speech datasets over different forms of dysarthria including spastic and ataxic cerebral palsy, Parkinson's disease and mixed dysarthria conditions, and also across varying speech disorder severity levels from mild, medium, high to very high. In the following research, we will continue to improve data augmentation techniques and curate more

disordered Cantonese speech data, as well as conduct further analysis of system performance over different forms of speech disorders and severity levels.

4. PUBLICATION AND AWARDS

[1] Shansong Liu, Shoukang Hu, Yi Wang, Jianwei Yu, Rongfeng Su, Xunying Liu and Helen Meng. Exploiting Visual Features using Bayesian Gated Neural Networks for Disordered Speech Recognition, **ISCA Student Paper Award Nomination**, ISCA Interspeech2019, Graz, Austria.
[2] Shansong Liu, Shoukang Hu, Xunying Liu and Helen Meng. On the Use of Pitch Features for Disordered Speech Recognition, ISCA Interspeech2019, Graz, Austria.
[3] Shoukang Hu, Shansong Liu, Hengfai Chang, Mengzhe Geng, Jiani Chen, Wingchung Lau, Kahei To, Jianwei Yu, Kaho Wong, Xunying Liu and Helen Meng. The CUHK Dysarthric Speech Recognition Systems for English and Cantonese, ISCA Interspeech2019, Graz, Austria.
[4] Rongfeng Su, Xunying Liu, Lan Wang and Jingzhou Yang. Cross-Domain Deep Visual Feature Generation for Mandarin Audio-Visual Speech Recognition, IEEE/ACM Transactions on Audio, Speech and Language Processing, Volume 28, Issue 1, December 2020, Pages 185-197. [DOI]
[5] Shoukang Hu, Sirui Xie, Hehui Zheng, Chunxiao Liu, Jianping Shi, Xunying Liu, Dahua Lin. DSNAS: Direct Neural Architecture Search without Parameter Retraining, to appear in IEEE/CVF CVPR2020, Seattle WA, USA.
[6] Shoukang Hu, Xurong Xie, Shansong Liu, Mengzhe Geng, Xunying Liu, Helen Meng. "Neural architecture search for speech recognition," in submission to ISCA Interspeech2020.
[7] Mengzhe Geng, Xurong Xie, Shansong Liu, Jianwei Yu, Shoukang Hu, Xunying Liu, Meng Helen. "Investigation of data augmentation techniques for disordered speech recognition," in submission to ISCA Interspeech2020.
[8] Shansong Liu, Xurong Xie, Jianwei Yu, Shoukang Hu, Mengzhe Geng, Rongfeng Su, Shi-Xiong Zhang, Xunying Liu, Helen Meng. "Exploiting cross-domain visual feature generation for disordered speech recognition", in submission to ISCA Interspeech2020.
[9] Jianwei Yu, Shixiong Zhang, Jian Wu, Shahram Ghorbani, Bo Wu, Shiyin Kang, Shansong Liu, Xunying Liu, Helen Meng, Dong Yu. AUDIO-VISUAL RECOGNITION OF OVERLAPPED SPEECH FOR THE LRS2 DATASET, **IEEE Signal Processing Society Travel Grant**, IEEE ICASSP2020, Barcelona, Spain.
[10] Jianwei Yu, Bo Wu, Rongzhi Gu, Shixiong Zhang, Lianwu Chen, Yong Xu, Meng, Yu, Dan Su, Dong Yu, Xunying, Liu, Helen Meng. "Audio-visual multi-channel recognition of overlapped speech," in submission to ISCA Interspeech2020.

COMPLETED

ACHIEVING SIMULTANEOUS SPECTRAL-SPATIAL SUPER-RESOLUTION VIA RECONSTRUCTION FROM MULTISPECTRAL AND HYPERSPECTRAL IMAGES

Principal Investigator: Professor Ken MA
Department of Electronic Engineering, CUHK

Research Team Members:
Qiang Li, Dr. [(1)], Ruiyuan Wu, Mr. [(1)]
Qiong Wu, Ms. [(1)], Huikang Liu[(1)]

[(1)] Dept. of Electronic Engineering, CUHK

Project Start Date: 1 July 2017
Completion Date: 30 June 2019

INNOVATION AND PRACTICAL SIGNIFICANCE:

This project aims to develop a theoretical framework for hyperspectral resolution, addressing why recovery of a hyperspectral super-resolution image from low resolution images can be possible in theory and further understanding how we can build better systems. While current developments in this context have shown successful results by empirical means, they are practice or intuition-driven and are unable to answer the question of why hyperspectral super-resolution works from a fundamental research viewpoint. The innovative part of this project is that the PI will depart from the standard path of the current research trends (which are somehow bottom-up) and endeavor to tackle much more challenging theoretical problems arising from this relatively new research topic (which is top-down with an emphasis on asking why, and not just how). The impacts are expected to be significant as it will lead to theoretical guidelines on designing provably good hyperspectral super-resolution algorithms and cameras, which is presently unavailable in the literature.

Moreover, the PI should emphasize that hyperspectral super-resolution is currently a rapidly emerging topic with great potential and many possibilities in applications such as computer vision, medical imaging, art conservation, to name a few. The PI sees that now is the great opportunity to investigate this timely topic, seeing the substantial impacts a theoretical framework can reshape the topic and the far-reaching implications in many applications.

ABSTRACT

Please state the abstract of the project in this part. The abstract should appear at the top of the report. All manuscripts must be in English.

Hyperspectral super-resolution (HSR), a recently emerged image processing technique that aims to reconstruct a spectral-spatial super-resolution image from images with either lower spectral resolution or lower spatial resolution, is expected to become a key technology soon. HSR can significantly enhance applications in areas such as computer vision, art conservation, food safety, geoscience and remote sensing, offering an imaging solution that can identify objects that are hard to see by human eyes and with fine resolutions. It holds great potential and we expect the topic will

see substantial growth. The goal of this project is to investigate key fundamental problems that arise in this timely topic. Specifically, the PI will study perfect reconstruction conditions of HSR—which is an open theoretical question that none of the existing literature has been able to answer. Addressing this question satisfactorily will lead to guidelines on how to build provably correct HSR solutions, rather than relying on empirical experience which is currently the case. Furthermore, the PI will study a unified optimization framework for HSR, which is important in establishing a computationally efficient algorithmic toolset in this context.

1. OBJECTIVES AND SIGNIFICANCE

Please state the objective and significance of the project in this part.

1. to analyze conditions under which perfect recovery of a super-resolution image is guaranteed, and to identify good low-rank models and provably correct formulations under such analyses

2. to establish a unified optimization framework for low-rank matrix factorization in HSR

The first objective of this project is particularly innovative. All the current developments in HSR demonstrate feasibility via empirical experiences, and the designs are intuition-driven. A theoretical framework that pins down whether and how super-resolution is possible is still missing—and the PI intends to challenge that piece of uncharted water. The outcomes, if satisfactory, will provide theory-guided designs for HSR, which has much significance from a fundamental research viewpoint and will reshape how practical researchers think when designing an HSR algorithm. The second objective is important in bringing new and computationally efficient tools for practical implementations.

2. RESEARCH METHODOLOGY

Please state the research methodology of the project in this part.

We consider low-rank matrix factorization for HSR---which is a widely adopted approach in the current HSR literature---and investigate two key aspects. First, we aim to answer an open theoretical question, namely, whether and under what conditions low-rank matrix factorization methods can guarantee perfect recovery of the true super-resolution image. Being able to address this question satisfactorily will lead to substantial impacts on developing good algorithms for HSR and on the designs of multispectral and hyperspectral camera. Currently, none of the existing literature is able to show that the low-rank matrix factorization problem can guarantee perfect recovery of the super-resolution image.

Second, we intend to establish a unified optimization framework for low-rank matrix factorization in HSR. The aim is to provide computationally efficient solutions for HSR. The problem size in HSR is large; e.g., a super-resolution image with 200 spectral bands and 1,000x1,000 pixels amounts to 200,000,000 unknowns. Careful designs that exploit problem structures are essential, and the framework should be flexible in being able to accommodate various forms of problem structure-exploiting regularizations. The outcome, if successful, will lead to a powerful computational toolset for practical implementations.

3. RESULTS ACHIEVED

Please state the project achievement in this part and (if any) please state the patent application

and/or product **commercialization plan**.

The PI is delighted to report that this project, which goes for the fundamental research track, is very successful. The PI would like to thank SHIAE for giving him the opportunity to try this fundamentally exploratory endeavor; without the support from SHIAE, the PI's accomplishment on the HSR research topic could have been much less.

While HSR is a practically important topic in hyperspectral imaging and remote sensing, with rapidly growing research activities as we noted lately, the theoretical aspects of HSR have been largely unexplored and not well understood. In layman language we are concerned with whether, in theory, we can perfectly recover a super-resolution image from lower resolution measurements from multispectral and hyperspectral sensors, and how this can be made possible. Our research can be regarded as pioneering attempts in "provably correct" HSR techniques. In J[1] and its conference versions C[2], C[5], we showed that perfect recovery can be accomplished by tensor factorization. It is worth noting that the tensor factorization approach proposed by us is a new approach for HSR. The work J[1] appears in IEEE Transactions on Signal Processing, the top journal in signal processing, in December 2018, and it appears to be receiving growing attention lately as indicated by the Google Scholar citations count.

Our another theoretical breakthrough has part of them presented, or to be presented, in C[3], [C6]. As promised in the project objective, we successfully showed why some existing or related matrix factorization methods can have perfect super-resolution image recovery. Those existing methods were intuitive inventions by engineers and lacked theory to support---previously. In answering the theoretical questions arising from this project, we now gave those existing methods a solid theoretical foundation on why they work. Now we also know how to go beyond the existing methods through much simpler designs; see C[3]. As a main post-project task, we are working on the complete version of C[3], C[6] as a journal article. The goal we set is high: to establish a complete theory for matrix factorization in HSR. No researcher has attempted this before, we have the results available and are organizing them with much excitement, and we hope that this work will make a (huge) difference.

We also made significant advances with the practical or algorithmic side of HSR. In the previously mentioned tensor factorization work J[1], we developed a new algorithmic solution that can allow us to bypass a technical issue, namely, the need to acquire the spatial decimation response in advance (which can be inconvenient in practice). In J[2] and its conference version C[4], we derived a new low-rank matrix estimation method that has robustness against some practical variability effects in real remote sensing environments. The work J[2], submitted to IEEE Transactions on Geoscience and Remote Sensing (among the top in remote sensing), is likely to be accepted based on our judgement with the first-round review comments. In J[3], submitted to IEEE Transactions on Signal Processing, and its conference version C[1], we built an efficient optimization framework for matrix factorization in HSR. The algorithms built from our framework are the fastest compared to the state-of-the-art algorithms, by our extensive experimental studies.

In summary, our research has led to a number of original and intriguing results. We dressed HSR, an important practice-driven topic in remote sensing and hyperspectral imaging, with a theoretical attire. In our view, our results substantially advanced the HSR techniques over the fundamental side. We hope that our results will have significant long-term implications, influencing how practical designers would design their systems from the hardware specifications, algorithms, to final integration. Again the PI is grateful to SHIAE for its generous support.

4. PUBLICATION AND AWARDS

Please list out and number all the publications and/or awards produced under the funded project. All these publications must be directly acknowledged the SHIAE funding support and stated the affiliation with the Institute. The list can be numbered in alphabetic order. When referring to them for the submission in CD, name the file with corresponding reference number in square brackets as "81150xx-J[1].pdf".

C[1] R. Wu, C.-H. Chan, H.-T. Wai, W.-K. Ma, and X. Fu, "Hi, BCD! Hybrid Inexact Block Coordinate Descent for Hyperspectral Super-Resolution," IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE, Calgary, Canada, pp. 2426-2430, April 15-20, 2018.

C[2] C. I. Kanatsoulis, X. Fu, N. D. Sidiropoulos, and W.-K. Ma, "Hyperspectral Super-Resolution via Coupled Tensor Factorization: Identifiability and Algorithms," IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE, Calgary, Canada, pp. 3191-3195, April 15-20, 2018.

C[3] Q. Li, W.-K. Ma and Q. Wu, "Hyperspectral Super-Resolution: Exact Recovery in Polynomial Time," IEEE Statistical Signal Processing Workshop (SSP), IEEE, Freiburg, Germany, June 10-13, 2018.

C[4] R. Wu, Q. Li, X. Fu and W.-K. Ma, "A Convex Low-Rank Regularization Method For Hyperspectral Super-Resolution," IEEE Statistical Signal Processing Workshop (SSP), IEEE, Freiburg, Germany, June 10-13, 2018.

C[5] C. I. Kanatsoulis, X. Fu, N. D. Sidiropoulos, and W.-K. Ma, "Hyperspectral Super-Resolution: Combing Low Rank and Matrix Structure," IEEE International Conference on Image Processing (ICIP), IEEE, Athens, Greece, October 2018.

C[6] H. Liu, R. Wu, and W.-K. Ma, "Is There Any Recovery Guarantee with Coupled Structured Matrix Factorization for Hyperspectral Super-Resolution?," 2019 IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing, IEEE, Guadeloupe, French West Indies, December 2020. Online available at https://arxiv.org/pdf/1907.12728.pdf

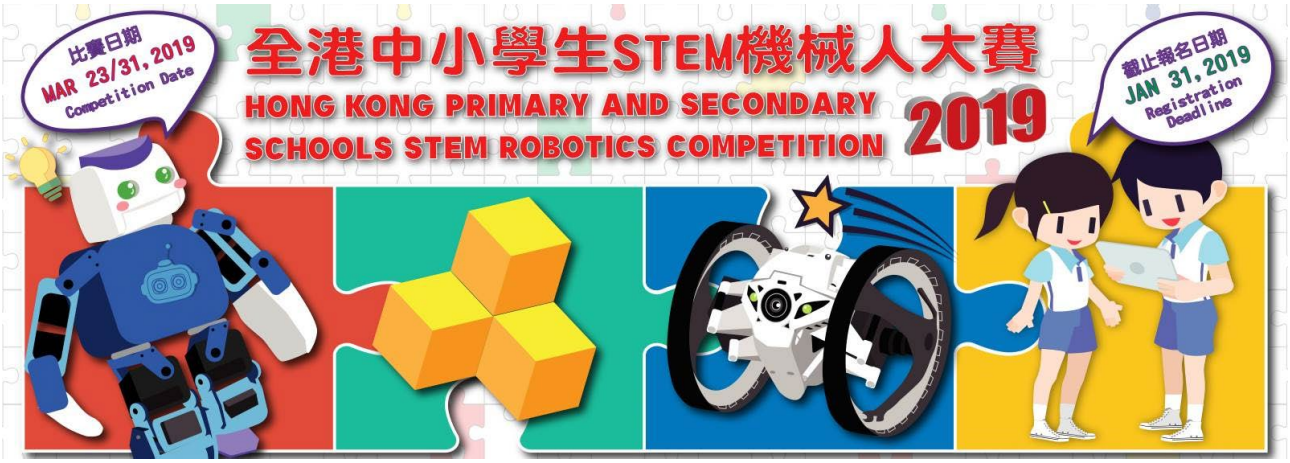
J[1] C. I. Kanatsoulis, X. Fu, N. D. Sidiropoulos, and W.-K. Ma, "Hyperspectral Super-Resolution: A Coupled Tensor Factorization Approach," IEEE Transactions on Signal Processing, vol. 66, no. 24, pp. 6503-6517, December 2018.

J[2] R. Wu, W.-K. Ma, X. Fu, and Q. Li, "Hyperspectral Super-Resolution via Global-Local Low-Rank Matrix Estimation," submitted to IEEE Transactions on Geoscience and Remote Sensing, June 2019, under first-round revision. Online available at https://arxiv.org/pdf/1907.01149.pdf

J[3] R. Wu, H.-T. Wai, and W.-K. Ma, "Hybrid Inexact BCD for Coupled Structured Matrix Factorization in Hyperspectral Super-Resolution," submitted to IEEE Transactions on Signal Processing, September 2019. Online available at https://arxiv.org/pdf/1909.09183.pdf

Educational Activities

To achieve the Institute's mission to promote appreciation of engineering in society and arouse interest of the younger generations in engineering through educational activities, the Institute has sponsored a **Hong Kong Primary & Secondary Schools STEM Robotics Competition 2019** and **Silicon Valley Technology Exploring Tour 2019**.



Hong Kong Primary & Secondary Schools STEM Robotics Competition 2019 has concluded successfully on March 31, 2019 in Engineering Faculty of The Chinese University of Hong Kong.

SILICON VALLEY TECHNOLOGY EXPLORING TOUR 2019
(22 July – 2 August 2019)

In 2019, the two winning teams of junior secondary division and four winning teams of senior secondary division were given opportunities to join the Technology Exploring Tour to Silicon Valley to visit well known institutions, enterprises and startups. The teams could sit down and discussed with their CTO and scholars, not merely a standard tour.

This is a non-traditional experiential learning activity for high school winners of the Competition and selected group of UG students sponsored and supported by SHIAE. The objective is to explore Hong Kong students to world-class science and engineering research, as well as the operation of leading technology ventures. Students had the opportunity to visit real work environments of technology giants, start-ups and research laboratories and to interact with technology and business leaders. During 10-day the tour at Silicon Valley, students were required to carry our thematic projects to analyze and solve problems posed by the host companies/ laboratories.

Schools visited:

Particle Physics, Stanford University
SLAC, Stanford University
Earth Science, University of California, Davis

Businesses visited:

Google Play e-book
August
Cisco
Flexera
NEXTeam Inc.
Leap.AI

Silicon Valley Technology Exploring Tour 2019 (22 July – 2 August 2019)

Here are the links of the video of activities:
https://youtu.be/j1fQWjvlmOM
https://youtu.be/rcv6nq-5_qE

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