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

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

Part A: The Project and Investigator(s)

1. Project Title

The Key Technologies Study for Deformable Bionic Search Robot with Electric Fabric Skin

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

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Professor Xiaoming Tao	Professor Zhong Su
Post	Chair Professor	Professor
Unit / Department / Institution	Institute of Textile & Clothing, The Hong Kong Polytechnic University	School of Information & Communication Engineering, Beijing Information Science & Technology University
Co-investigator(s) *(with title)*	Professor Danilo De Rossi	Professor Lihua Dou Professor Qing Li

3. Project Duration

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

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. To design, fabricate and evaluate artificial deformable structures of flexible search robot capable of changing its length, width and height; to investigate its deformable mechanisms and develop control algorithm in disaster search conditions;
2. To design, fabricate and characterize water-proof, abrasion-resistant fabric composite skin with embedded rigid miniature sensors and stretchable resistive fabric sensor arrays or matrixes for sensing distributions of environmental conditions such as temperature, humidity, noxious gas and mechanical stress/strain. To develop a new type of flexible large-area fiber sensor array or matrix based on fiber diodes or transistors and compare these two types of electric fabric skins;
3. To design, fabricate and evaluate a new type of electro-active polymer actuators characterized by low voltage and fast response to mimic the serpentine or wriggling of a snake;

4. To build up a SLAM (Simultaneous Localization and Mapping) algorithm based on extended Kalman filer and stereoscopic vision to plan the route of deformable bionic search robot in unstructured environment;
5. To integrate and evaluate the deformable bionic search robot system with electric fabric skin that can autonomous plan its route in natural disasters by combining deformable mechanical structures, sensitive electric fabric skin, dielectric elastomer actuators and SLAM algorithm.

5.2 Revised Objectives

N/A

6. Research Outcome

6.1 Major findings and research outcome

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

FCB, a new type of flexible circuit boards, an essential component of wearable electronics, is the central piece of investigation. Fabricated by using computerized knitting technologies at ambient dry conditions, the resultant knitted fabric circuit boards (FCBs) exhibit outstanding electrical stability with less than 1% relative resistance change up to 300% strain in uni-directional tensile test or 150% membrane strain in three-dimensional ball punch test, extraordinary fatigue life of more than 1,000,000 loading cycles at 20% maximum strain, and satisfactory washing capability up to 30 times. The benchmark analysis shows that the performance of new FCBs has far exceeded those of previously reported elastomeric films coated with metals or other organic materials in terms of changes in electrical resistance, stretchability, fatigue life and washing capability as well as permeability [Li and Tao, 2014].

Structural mechanic analysis of the FCBs has been carried out based on Leaf' knitted fabric model. The effects of yarn diameter, elastic modulus and fabric structure have been numerically examined by finite element method. Theoretical analysis and numerical simulation reveal the mechanism responsible for the remarkable performance. The structural conversion of knitted fabrics is attributed to the effective mitigation of strain in the conductive metal fibers thus the outstanding mechanical and electrical properties. These distinctive features make the FCBs particularly suitable for next-to-skin electronic devices. This work has been selected by Royal Society Proceeding A as the cover story in Sept. 2014. Since its publication, major scientific media in USA, UK, China and Australia have reported this work. A US patent was applied and subsequently granted.

The electronic skins built on the FCB are found as more suitable for search robots and human than the optical skins integrated with fiber grating sensing network, because of the ease of system integration and small size. However, the optical skins have a higher accuracy and higher sensitivity at stress levels lower than 6 KPa. They are appropriate for robots with limited movement and smart mannequins. Based on the finding of the comparative study, an industrial sponsored ITF project was granted to develop smart leg mannequins for evaluation of medical compression stockings [Tao et al. 2015, 2016].

Extended from the FCB technology, we further integrated stretchable fabric strain sensors into electronic skin for monitoring movement of robots and human subjects [Wang et al, 2016, 2017]. A PhD student has followed this topic and completed his study in 2017. A

completed wearable system was developed based on a new fully verified bio-mechanical model for human muscle-skeleton of upper arms. An ITF project was granted to fully develop a wireless limb gauge measurement system that was used in trials at the Hong Kong Sports Institute. Two journal papers were published.

The research on artificial muscles have made steady progress. One MPhil student just finished his thesis on thermos-electrical linear actuators in August 2017 and is waiting for oral examination. One PhD student started his work in the same direction in September 2017. Two journal papers are under preparation.

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

The huge potential for applications has encouraged Prof. Tao to further develop the research. ITF funding supports have been secured for two projects and two more students joint in the team.

7. The Layman's Summary

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

This project has investigated the key technologies of novel deformable bionic search robot with electric fabric skin that can sense environmental conditions real-time dynamic data of temperature, humidity, noxious gas and mechanical stress/strain, plan routes, based on information obtained from the sensors and camera, by SLAM algorithm, and vary its size and structure to adapt different routes in narrow space. The deformable bionic search robot with the electric fabric skin to be created and investigated in the project can provide full autonomous route planning and behavior control as they have whole-space sensing capacity.

Five complex and challenging tasks have been accomplished. The first is novel deformable mechanical structures that can adjust its shape such as height, width and length to adapt the search route. The second is the stretchable electric fabric skin which can satisfy the deformation of the robot without damaging the whole-space sensing capabilities of physical quantity such as temperature, humidity, noxious gas, etc. The third is the bionic dielectric elastomers actuator which can drive the bionic search robot in snake-like or worm-like motion and their driving device/ control algorithm in low voltage and fast response. The fourth issue is the algorithm to planning the search route autonomously. The final task is a novel prototype bionic search robot based on the knowledge and technology developed in former four parts.

Part C: Research Output to date

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

(please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge funding support from this scheme by quoting the specific grant reference.)

The Latest Status of Publications				Author(s) ***(bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Title and Journal/Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*					
2014				Li Q and Tao XM*	Three-dimensionally deformable, highly stretchable, permeable, durable and washable fabric circuit boards/ Royal Soc. Proceedings A, 470, 20140472	2014	No	yes
2016				Wang X, Tao XM* and RCH So	Monitoring elbow isometric contraction by novel wearable fabric sensing device, Smart Materials and Structures, 25(12), Article No. 125022.	No	Yes	Yes

2017				Wang X, Tao XM* and RCH So	A Bio-mechanical Model for Elbow Isokinetic and Isotonic Flexions, Scientific Report, 7(1), 8919.	No	Yes	Yes

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

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*
05/2015/Chongqing, China	Soft Deformable Electronic Skin for Bionic Robots	4th International conference on Advanced Materials	No	Yes	Yes
06/2016/Perugia,Italy	Interfacial force mapping by smart artificial skins	CIMTEC 2016	No	Yes	Yes

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

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Wang Xi	PhD	18/10/2013	17/10/2016

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

A US patent was applied in 2013 and granted in 2017. Stretchable electrical interconnect and method of making same, US 975259.

The results of the project has led to successful application of two ITF projects: (1) to develop the wearable training system for elite sportmen with Hong Kong Sports Institute; (2) to develop a new evaluation system for medical compression stockings by constructing smart leg mannequins covered by flexible optical smart skins.

Dr. Wang Xi participated in an international research student paper competition organized by Fiber Society, USA, November 2017. He was awarded the Second Prize.