RGC Ref.:
E-PolyU502/17

European Commission (EC) / Research Grants Council (RGC) Collaboration Scheme

Completion Report

(Please attach a copy of the completion report submitted to the European Commission by the project coordinator of the concerned Horizon 2020 project)

Part A: The Project and Investigator(s)

1. Project Title

Virtual Spindle based Trans-scale Tool Servo Diamond Cutting of Hierarchical Optical Surfaces

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

	Hong Kong Team	Europe Team
Name of Principal Investigator / Project Coordinator *(with title)*	Prof TO Sandy Suet	Dr RIEMER Oltmann
Post	Professor	Professor
Unit / Department / University	Industrial and Systems Engineering / The Hong Kong Polytechnic University	Laboratory for Precision Machining / University of Bremen
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Co-investigator(s) *(with title and institution)*	Prof ZHU Zhiwei Dr CHENG Tong Cheung	

3. Project Duration

	Original	Revised	Date of RGC/ University Approval *(must be quoted)*
Project Start date	1 Apr 2018	N.A.	
Project Completion date	31 Dec 2020	30 Jun 2021	10 Dec 2020
Duration *(in month)*	33	39	10 Dec 2020
Deadline for Submission of Completion Report	31 Dec 2021	30 Jun 2022	10 Dec 2020

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1) To propose a superior diamond tool based manufacturing strategy to overcome certain inherent limitations in the state-of-the-art cutting techniques for the generation of hierarchical optical surfaces;
2) To develop a novel trans-scale tool servo (TSTS) system, and the methodology for optimal mechanical design and servo system design for the realization of the TSTS system for micro/nano-manufacturing;
3) To propose the surface slicing strategy from the viewpoint of spindle virtualization, and to investigate the optimal toolpath generation and the scale-based motion re-arrangement algorithms for the virtual spindle based TSTS system;
4) To reveal the underlying surface generation and material removal mechanism with full consideration of the kinematic and dynamic properties of the virtual spindle based TSTS system as well as material properties.

5.2 Revised Objectives

N.A.

6. Research Outcome

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

The virtual spindle principle has been proposed and demonstrated through both theoretical simulation and experimental test. Through practical cutting, hierarchically micro/nanostructured optical surfaces as well as fluidic channels were generated. The superiority of this new principle was well demonstrated in terms of machining accuracy, machining capability, and machining flexibility [1]. The concept of trans-scale tool servo was proposed by combining both slow motion with large stroke and fast motion with short stroke. To construct the mechatronics system, Lorentz force based electromagnetic the trans-scale motion [2]. A two-degree-of-freedom vibration generator (2DOF-VG) was designed based on the quasi-ellipse amplification unit [3]. A numerical simulation algorithm of the microstructure arrays generation was then established by multi-physics finite element method and used to precisely predict the surface topography of microstructure arrays. Periodic saw-tooth-like microstructures were fabricated on pure magnesium surfaces [4]. Two groups of viewing-angle-dependent structural colors (i.e. coral color and green color; blue color and magenta color) were clearly observed with high saturation. Furthermore, a hybrid control strategy was proposed where the piezoelectric actuator and Lorentz force-based actuator were controlled through open-loop and closed-loop controllers. Specially, the slow dynamics of the Lorentz force actuator was compensated through the piezoelectric actuator system. Based on the characteristics of the desired surface, the spindle center determination algorithm was proposed, and the theoretical toolpath was derived with the constraint from surface generation accuracy. Moreover, the process parameters were deliberately selected to generate the specified nanostructures superimposed on the primary surfaces. Through geometry calculation, the surface generation algorithm was proposed with full consideration of the special kinematics of the TSTS system. The cutting force model was also established through considering the material property, tool geometry, friction characteristic, and thermo effects. A novel TSTS system was developed to improve the actuation and control performance for cutting, and advanced control strategy was developed for accurate trajectory tracking. In addition, experiments were conducted to make analysis of toolpath decomposition algorithm for targeting better tracking accuracy.

A dynamic surface generation model was established by considering the coupling effect between the servo axis dynamics and the cutting force [5]. Using a micro-lens array (MLA) as an example, the components of the servo dynamics error of the servo motion, including dynamic deformation, resonant vibration, and trajectory tracking error, were characterized. The relationship between the servo dynamics error and the resulting form error was then theoretically identified with experimental verification. To compensate for the servo dynamics error in real-time, the concept of a cooperative tool servo (CTS) was proposed by incorporating a slow tool servo (STS) into a fast tool servo (FTS) using a master-slave control strategy. A novel direct drive XY nano-positioning stage was designed by adopting a newly developed dual-axial normal-stressed electromagnetic actuator [6]. The mechanical- electromagnetic parameters of the stage were determined with the assistance of the established analytical model, which were then comprehensively verified through finite element analyses. To ultra-precisely track periodic trajectories for the stage, a PID-based controller with a parallel resonant controller was developed for each axis, and an error less than ±0.42% was obtained when tracking a Lissajous trajectory. A novel normal-stressed electromagnetic triaxial FTS was further developed, which has a single armature to provide the triaxial decoupled and non-contact driving forces, as well as a symmetric 3-DOF corrugated compliant bearing, to support and guide the decoupled outputs [7]. A linear active disturbance rejection controller combining an iterative learning scheme was further employed to achieve fast and accurate trajectory tracking. The developed triaxial FTS was comprehensively demonstrated by fabricating a hexagonal spherical micro-lens array, and a good surface quality with a form error of 63.66 nm and surface roughness of Sa=2.05 nm was achieved.

During this report period, four more papers have been submitted to the journals and are accepted. Six papers have been accepted in total. In addition, one manuscript has been submitted to an international journal and is under review.

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

More various complicated micro-nano structures can be fabricated by the newly developed machining strategy, methods or systems. The functions of different designed micro-nano structures generated can be explored and tested further for various applications in real life.

7. The Layman's Summary

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

Trans-scale tool servo (TSTS) from virtual spindle principle has been proposed and demonstrated through both theoretical simulation and experimental test. Hierarchically micro/nanostructured optical surfaces and fluidic channels can be generated. To construct the equipment, a TSTS device was developed by cascading a Lorentz force-based actuator with a piezoelectric actuator, and a master-slave control strategy was developed to enhance the working bandwidth and accuracy for the tool. Besides, novel direct drive dual-axial TSTS system was proposed by adopting a newly developed dual-axial normal-stressed electromagnetic actuator. To reveal the material removal behavior, a comprehensive cutting force model was established including material property, tool geometry, friction characteristic, and thermo effects. To describe the surface generation mechanism, a dynamic surface generation model was established by considering the coupling effect between the servo axis dynamics and the cutting force. Based on the established model, the main error sources were identified and experimentally validated, and a real-time error compensation strategy was proposed and demonstrated by fabricating typical microlens arrays. All these newly developed machining methods and systems greatly enhance machining accuracy, machining capability, and machining flexibility in ultra-precision machining through the demonstration of machining complicated micro-structures, including diffractive lenses, micro-lens arrays, hierarchically micro/nanostructured optics.

Part C: Research Output

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

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

The Latest Status of Publications				Author(s) (***bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Title and Journal/ Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this collaboration scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*						
[1] 2020	2019			Peng Huang, Hongcheng Li, Wu-Le Zhu, Haitao Wang, Guoqing Zhang, Xiaoyu Wu, **Suet To**, **Zhiwei Zhu***	Effects of eco-friendly cooling strategy on machining performance in micro-scale diamond turning of Ti-6Al-4V, *Journal of Cleaner Production, 243, 118526.*	Yes (2019)	Yes	Yes	Yes
[2] 2020	2019			**Zhiwei Zhu**, Li Chen, Peng Huang, Lars Schoneman n, **Oltmann Riemer**, Jainyong Yao, **Suet To**, and Wu-Le Zhu*	Design and control of a piezoelectrically actuated fast tool servo for diamond turning of micro-structured surfaces, *IEEE Transactions on Industrial Electronics, 67, 8.*	Yes (2019)	Yes	Yes	Yes

[3] 2021	2021			Hanheng Du, Wai Sze Yip, **Zhiwei Zhu**, and **Sandy To***	Development of a two-degree-of-freedom vibration generator for fabricating optical microstructure arrays, *Optics Express*, 29, 16, 2, 25903-25921.	No	Yes	Yes	Yes
[4] 2021	2021			Hanheng Du, Tengfei Yin, Wai Sze Yip, **Zhiwei Zhu**, and **Suet To***	Generation of structural colors on pure magnesium surface using the vibration-assisted diamond cutting, *Materials Letters*, 299, 130041.	No	Yes	Yes	Yes
[5] 2020	2020			Peng Huang, Xiaoyu Wu, **Suet To**, LiMin Zhu, **Zhiwei Zhu***	Deterioration of form accuracy induced by servo dynamics errors and real-time compensation for slow tool servo diamond turning of complex-shaped optics, *International Journal of Machine Tools and Manufacture, 154, 103556.*	No	Yes	Yes	Yes

[6] 2021	2021			**Zhiwei Zhu**, Li Chen, **Suet To***	A novel direct drive electromagnetic XY nanopositioning stage, *CIRP Annals – Manufacturing Technology, 70, 415-418.*	No	Yes	Yes	Yes
[7] 2022	2022	Revised		Yanning Fang, Xiaonan Pu, **Suet To,** Bernard Hon, Li-Min Zhu, **Zhiwei Zhu**	Normal-stressed electromagnetic triaxial fast tool servo for micro-cutting, *IEEE Transactions on Industrial Electronics*	No	Yes	Yes	No

9. Recognized international conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper. All listed papers must acknowledge RGC's funding support by quoting the specific grant reference.)*

Month/Year/Place	Title	Conference Name	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this collaboration scheme *(Yes or No)*	Accessible from the institutional repository *(Yes or No)*
2019	Ultra-Precision Machining of Hierarchical Micro-Nanostructures and Its Application	The 8th International Conference of Asian Society for Precision Engineering and Nanotechnology (ASPEN 2019)	No	Yes (Keynote Speaker)	Yes	No

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

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation
Hanheng Du	PhD	2nd Sept 2019	18th May 2022

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

Our project team has participated in a European research collaboration project entitled "High Precision Process Chains for the Mass Production of Functional Structured Surfaces" funded by the Horizon 2020 from the European Commission (EC). Project members included 13 institutes, universities, and companies from seven different countries. In the Horizon 2020 project, POLYU has proposed a virtual spindle-based tool servo (VSTS) diamond turning method for generating discontinuously structured micro-optics arrays. VSTS has been applied to manufacture a copper mould insert with micro-flat head pits with spiral features for a mass production of micro-pillars by plastic injection moulding. The surface topographies of the mould insert and the moulded samples including SEM images and 3D profiles with cross sections have been characterized. With consideration of different shapes of diamond cutting tools, it can greatly increase the flexibility of the structure design for achieving a demonstrator of transparent hydrophobic micro-patterned surface.

12. Statistics on Research Outputs

(Please ensure the summary statistics below are consistent with the information presented in other parts of this report.)

	Peer-reviewed journal publications	Conference papers	Scholarly books, monographs and chapters	Patents awarded	Other research outputs (Please specify)
No. of outputs arising directly from this research project	7	1	0	0	0