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Research Assessment Exercise 2020
<u>Impact Case Study</u>

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University: The Hong Kong University of Science and Technology
Unit of Assessment (UoA): 12 electrical & electronic engineering
Title of case study: Improvements in the motion control design of industrial robots

(1) **Summary of the impact**
Research by Professor Zexiang Li at HKUST has resulted in the development of three technologies addressing critical issues in motion and robot control: a tolerance-based motion control system, a novel adjoint error based calibration algorithm, and a systematic approach to dynamics based control. Together, these technologies enable motion controllers with better accuracy, faster response and higher efficiency. All three technologies have been adopted by the controllers of Googol Technology Ltd, a start-up company founded by Prof. Li. This has improved their performance well beyond that of its competitors, leading to significantly increased sales during the census period.

(2) Underpinning Research

Research by Prof. Zexiang Li at HKUST from 2006-2016 has addressed three major issues encountered in the traditional design of computer numerical control (CNC) and robot control systems.

First, Prof. Li proposed a new concept, a tolerance-based motion control (TMBC) system, which consists a tolerance-based motion generation (TBMG) module and a TBMC module. The TBMG module takes the desired level of tolerance and calculates the maximum permissible feed-rate based on the trajectory, the machine characteristics and the desired tolerance level. The TBMC module minimizes the profiling error, a major part of the contouring error. Li's students developed this concept further. Zhang found that the contouring error was quite difficult to measure, so approximated it by projecting the tracking error to the normal subspace [1]. Lou incorporated the error dynamics of the contouring error into the formalism by attaching a task frame that moves along the machining trajectory [2]. The resulting algorithm exhibits a much better contouring accuracy. In collaboration with the Harbin Institute of Technology (HIT) in China, Li and his students also researched advanced algorithms for trajectory generation that decrease machining error further, such as a real-time cubic parametric curve interpolation algorithm that enables CNC systems to handle complicated curves [3].

Second, Li developed a novel algorithm, Adjoint Error Based Calibration**,** which improves industrial robot accuracy by calibrating kinematics parameters using manifold theory. By introducing a general Adjoint Error, Li was able to unify the treatment of many kinds of errors, enabling easier and more efficient calibration of robot parameters [4]. Li's students, Yubo Zhan and Dan Dai, successfully transferred the algorithm into reality. In his master's thesis [5], Zhan developed Gibbon, a novel and low-cost (approximately one quarter of that of similar products) piece of equipment composed of a wire draw encoder and magnetic encoder, for user-friendly calibration of robot parameters. This calibration enhances accuracy significantly, from 5mm to 0.3mm. This meets the needs of the majority of industrial robot applications. The calibrated performance is comparable to that of products from internationally well-known companies, such as Yaskawa, Kawasaki and ABB.

Third, Li systematized an approach to dynamics-based trajectory optimization and control of industrial robots. Dynamics-based control algorithms lie at the boundary between low-level and high-level robot controllers. They can overcome the limitations of traditional control strategies, such as instability and vibration in the case of high loop gain and poor tracking performance in the case of small loop gain. They also improves the performance of industrial robots. For example, ABB always claims that its mode-based controller, FANUC, optimizes for robot structure and motor type by considering robot dynamics. In his PhD thesis [6], Li's student Dan Dai developed a systematic

algorithm based on a geometric method for applying robot dynamics. This algorithm first estimates a minimal set of identifiable dynamical parameters. It then considers dynamical constraints along a specific path to optimize the robot velocity and acceleration and to utilize the motor output power optimally. This makes robot trajectories more energy efficient and time optimal.

(3) References to the Research

[1] DJ Zhang, YJ Lou and ZX Li, Geometric contouring control on the smooth surface, presented at the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4496 – 4501, Oct. 2006.
[2] YJ Lou, N Chen and ZX Li, Task space based contouring control of parallel machining systems, presented at the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2047 – 2052, Oct. 2006.
[3] JG Li, L Zhou, TH Zhang and ZX Li, A real-time cubic parametric curve interpolations for CNC systems, presented at the 7th World Congress on Intelligent Control and Automation, Chongqing, China, 2008
[4] YJ Lou, TN Chen, YQ Wu, ZB Li and SL Jiang, Improved and modified geometric formulation of POE-based kinematic calibration of serial robots, presented at the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 5261–5266, 2009
[5] Yubo Zhan, Development of a Wire Draw Encoder based Measurement System for Robot Calibration, Master thesis, Department of ECE, HKUST, 2015
[6] Dai Dan, A Systematic Procedure for Applying Robot Dynamics-based Control, PhD thesis, Department of ECE, HKUST, 2016

(4) Details of the Impact

Googol Technology Ltd was founded in 1999 by three professors from HKUST: Zexiang Li, Bingqiang Gao and Hong Wu [A]. Since its establishment, the company has aimed to improve the manufacturing level of China's industry. By supplying both excellent engineers and leading technologies, HKUST has enabled GoogolTech to become a major supplier of motion controllers, covering a wide range of industrial applications in China and fulfilling the company's original ambitious goal.

GoogolTech has absorbed many outstanding young researchers nurtured by HKUST and assigned them to core positions within the company. These include Shu Lv (the vice manager of GoogolTech Ltd), Zhang Tinghua (the vice manager of the motion controller research department), Yue Liu and Dan Dai (the manager and vice manager of the robot business department), and Junheng Chen (the manager of the CNC business department). Expert advisors to the company, such as Professors Yunjiang Lou and Jianggang Li of HIT, are also Li's early students. Ling ZHOU, Director of Googol Technology (HK) Limited states that "Many Ph.D. and Masters students trained by Prof. Li have joined the company… they have made significant contributions to the company's strength in R&D to enhance products and functionality" [B].

The major products of GoogolTech derived from HKUST's research include high performance controllers, drivers and sensors. Customers apply its controllers in many areas, such as CNC machines, industrial robots, laser cutting, injection moulding, and semiconductor and microelectronics manufacturing. GoogolTech's annual sales of motion controllers now total around USD 40 million, representing about 41% of the market share in China [C]. To meet customer requirements in different areas and to provide tailored services and products, GoogolTech has established ten branches in China, including branches in Taiwan, Beijing, Shanghai, Suzhou and Xian. In addition, inspired upon its successful technology transfer from HKUST, GoogolTech has adopted Li's goal of accelerating

cooperation between local government, universities and enterprises to translate research achievements into practice, by supporting several research centres including centers in Chongqing, Shanghai and Zhuhai.

Li's TMBC algorithm is the foundation of GoogolTech's CNC motion controller, which has been a huge success and has surpassed the majority of domestic CNC motion controllers in China. It now competes with those from internationally well-known companies such as Siemens, Fargo and FANUC. Figure 1 shows the increase in sales units of GoogolTech's CNC controllers over six years after integrating advances advanced control and trajectory planning algorithms.
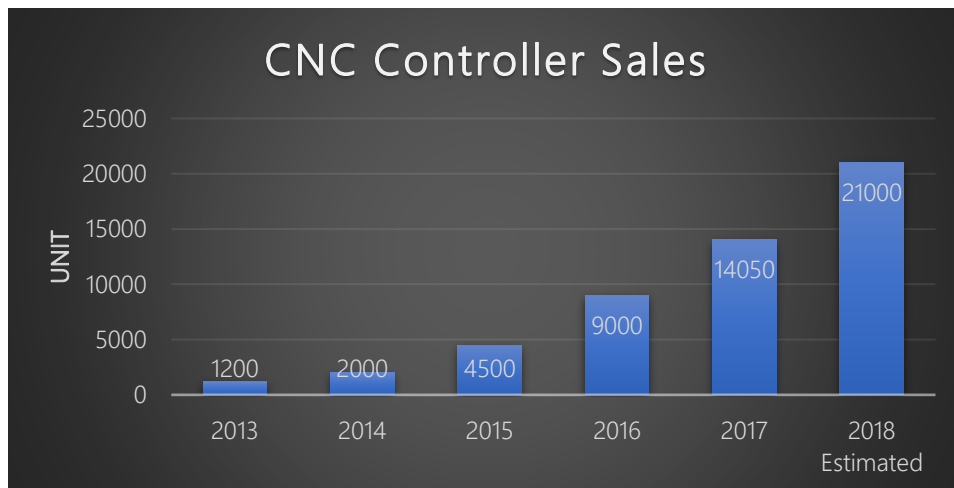

Figure 1. Growth in Googoltech's CNC controller sales since 2013

GoogolTech has also adopted Li's kinematic calibration and dynamics-based control algorithms into its robot controllers. Director ZHOU states "an extremely challenging problem in the calibration of industrial robots was solved for the first time… by Prof. LI's group and Googoltech's R&D team" [B]. Kinematic calibration has decreased GoogolTech's robot-tracking errors dramatically, by at least a factor of two. Director ZHOU further states "a collaboration between HKUST and the Googletech team found the solution to a long-standing problem in the dynamic control of industrial robots" [B]. This not only makes robots using GoogolTech's controllers more stable, it also gives them a quicker dynamical response. Their gold standard equipment is the Wire Draw Calibration Equipment developed by Li's MPhil student, Yubo Zhan. The line accuracy of GoogolTech's Robot Controller System outperforms that of Yaskawa. As Figure 2 indicates, sales of GoogolTech's robot controllers have increased steadily to the point that they dominate the China market. Director ZHOU concludes, "the technologies developed by Prof. Li's group and research centre in HKUST have helped Googoltech to become a leader of the robotics industry in China in terms of both brand recognition and market share" [B].

HKUST leading technologies have also led to other achievements by GoogolTech during the census period [D]. These include:

2014   GoogolTech wins the National Science and Technology Progress Award (Second class, semiconductor)
2015   GoogolTech was introduced as the 'Chinese Technology Little Giant' by Chinese CCTV
2016   GoogolTech wins the National Science and Technology Progress Award for the second time (Second class, textile)
2017   GoogolTech wins First Prize in the China Machinery Industry Science and Technology Award
2018   GoogolTech's Marvie 6-axis drive integrated robot controller wins the Drive & Execute Product Award from China Gongkong.com 2018
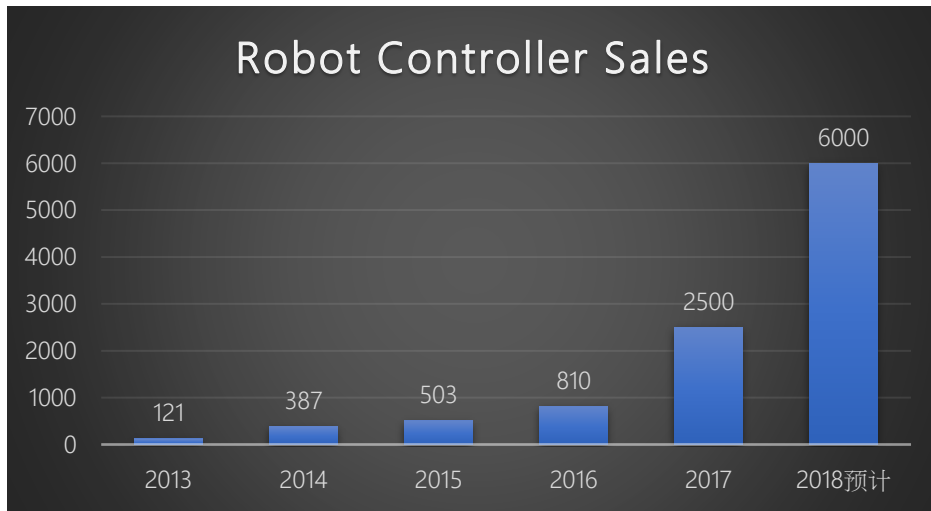
Figure 2. Googoltech's robot controller sales in recent years (sales in 2018 were estimated)

(5) Sources to corroborate the impact
[A] Description from Googol Technology website: www.directindustry.com/soc/googol-technology-hk-limited-85573.html
[B] Letter from Ling ZHOU, Director of Googol Technology (HK) Limited.
[C] China market share of PC-based controller in 2017: 40.7% (Data source: www.gongkong.com)
[D] Major award list