Institution: University of Oxford

Unit of Assessment: 10: Mathematical Sciences

Title of case study: Rough Path signature analysis for recognition of Chinese handwriting

Period when the underpinning research was undertaken: 2000 - 2017

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Terry Lyons	Professor	2000 - present
Ben Hambly	Professor	2000 - present
Lajos Gergely Gyurkó	PDRA	2013 - 2014
Hao Ni	PDRA	2012 - 2016
Harald Oberhauser	PDRA, Associate Professor	2013 - 2014, 2015 - present

Period when the claimed impact occurred: 1 October 2014 – 31 July 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Rough Path signature analysis, developed at the University of Oxford, has been combined with neural net machine learning techniques to produce a mathematical methodology that has enabled accurate and efficient recognition of finger-drawn Chinese characters in real-time on mobile devices.

This combined approach has been implemented as a mobile phone app (or more precisely a mobile phone "keyboard" for apps) for the real-time entry of Chinese characters by an Information Engineering team at the Southern China University of Technology. The initial keyboard app, which has been downloaded by over 1,000,000 users, is now licensed to Sogou, a major Chinese corporation, and underpins their market-leading keyboard app which is used by approximately 60% of all Chinese smartphone users, with an estimated 75,000,000 people using the handwriting recognition features each day.

2. Underpinning research

Rough Path theory is an area of mathematics that has been developed by researchers at the University of Oxford led by Professor Terry Lyons. Rough Path theory provides a toolset that can describe the interactions between complex and highly oscillatory data streams (rough paths) in the same way that Newton's differential calculus described the interactions between elements evolving with smooth trajectories.

Within this body of research, one key idea, introduced in the landmark paper [1], is the use of "signatures" and "log-signatures", which are nonlinear transformations of complex multimodal streams of data which capture or represent the key features of the data. Lyons and the team at the University of Oxford have developed the signature into a tool of mathematical significance which can be used directly for the analysis of real world data streams [2,3,4]. In particular, [2,3] describe early work on the use of signatures as a viable tool for data science, ahead of the large-scale adoption of deep learning and neural net techniques. This research was supported over the period 2012-2017 by an ERC Advanced Grant.

In 2015, Lyons and his team began a collaboration with Professor Lianwen Jin from the Information Engineering Department at the Southern China University of Technology (SCUT) on the use of a combination of rough path signatures and sparse convolutional neural nets for online Chinese handwriting recognition. Two key advances followed. Firstly, a dyadic path signature feature was introduced to fully characterize the trajectory of the pen tip on the smartphone using a hierarchical structure, and also achieve rotation-free online handwriting

character recognition; this was presented at the leading IEEE conference in 2016 [5]. Secondly, the capability of path signature to translate online pen-tip trajectories into informative feature maps using sliding-window-based methods was established which, with an implicit semantic prediction step, give outstanding results that significantly boost character recognition rates for two standard datasets (Dataset-CASIA and Dataset-ICDAR) [6].

3. References to the research

[1] Hambly, B., Lyons, T., "Uniqueness for the signature of a path of bounded variation and the reduced path group", *Annals of Mathematics*, 171(1):109-167, 2010, DOI: 10.4007/annals.2010.171.109

[2] Gyurkó, L.G., Lyons, T., Kontkowski, M., Field, J., "Extracting information from the signature of a financial data stream", *arXiv* paper 1307.7244v1, 2013

[3] Lyons, T., Ni, H., Oberhauser, H., "A feature set for streams and an application to high-frequency financial tick data", *Proceedings of the 2014 International Conference on Big Data Science and Computing, ACM,* 2014, DOI: 10.1145/2640087.2644157

[4] Lyons, T., "Rough paths, Signatures and the modelling of functions on streams", In *Proceedings of the International Congress of Mathematicians: Seoul*, pp.163-184, 2014, *arXiv* paper 1405.4537

[5] Yang, W., Jin, L., Ni, H., Lyons, T., "Rotation-free online handwritten character recognition using dyadic path signature features, hanging normalization, and deep neural network", *Proceedings of the 23rd International Conference on Pattern Recognition, IEEE*, 2016, DOI: 10.1109/ICPR.2016.7900273

[6] Xie, Z., Sun, Z., Jin, L., Ni, H., and Lyons, T., "Learning spatial-semantic context with fully convolutional recurrent network for online handwritten Chinese text recognition." *IEEE Transactions on Pattern Analysis and Machine Intelligence* 40(8):1903-1917, 2017, DOI: 10.1109/TPAMI.2017.2732978

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EPSRC grant EP/F029578/1: *Rough path analysis and non-linear stochastic systems*, 2008-2011, GBP293,702. PI Terry Lyons
ERC Advanced Grant 291244: *Creating rigorous mathematical and computational tools that can summarise high dimensional data in terms of their effects*, 2012-2017, EUR1,814,301. PI Terry Lyons.

4. Details of the impact

The research into Rough Path signatures carried out at the University of Oxford has resulted in economic impact for Sogou, a major Chinese corporation, and has enabled an estimated 75,000,000 people in China to daily input accurately Chinese characters into their smartphones by drawing on the screen. This has resulted in societal benefit particularly to older Chinese users by enabling them to fully embrace the internet through their smartphones.

Sogou is a Chinese internet company which was spun off from a company called Sohu.com in 2010 [A]. It is best known for two things: its search engine, which is number two in the Chinese market with roughly a 20% market share compared to about 70% for Baidu [B], and its Mobile Keyboard (previously known as Sogou Input Method) which is a utility for mobile phones through which users can input Chinese characters [A]. The great success of the keyboard product came from Sogou's development of an interface for Pinyin, a Romanization of the Chinese characters based on their pronunciation; this is extremely popular amongst younger users and made the Mobile Keyboard the market leader in this area [A]. Sogou is a Beijing-based public company. Until recently it was listed on the New York Stock Exchange but in September 2020 it was acquired by Tencent, one of China's largest internet companies, for more than USD2,000,000,000 [B].

Pathway to impact

In 2012, Lyons had discussions with Ben Graham (then at University of Warwick, now at Facebook) who was pioneering the development of sparse neural network techniques. Graham also had an interest in Chinese character recognition, and Lyons' recent work on signatures led Graham to combine signature annotation of pen strokes with his sparse neural net methods. With this combination, Graham won one part of an international competition on Chinese handwriting recognition as part of the IEEE 12th International Conference on Document Analysis and Recognition (ICDAR). His accompanying 2013 paper ("Sparse arrays of signatures for online character recognition") cites four of Lyons' papers, including [1].

The successful combination of signatures and neural nets for Chinese character recognition immediately attracted the attention of Prof Lianwen Jin, a computer scientist at SCUT who in 2015 was Dean of Information Engineering in SCUT's School of Electronic and Information Engineering, and also head of the HCII (Human-Computer Intelligent Interaction) lab. Jin led a team working on handwriting recognition using other methods, but he was also aware of machine learning techniques. As Jin explains [D]: "*We have for many years been a leader in the technology of document analysis and optical character recognition, and particularly online entry of finger drawn Chinese handwriting. It was a breakthrough when Ben Graham introduced his prize winning technology in this area, combining path signatures with sparse convolutional neural networks. We very quickly introduced and further developed use of the combination of signature and traditional features in our approach. The successful application of signature feature in our work was inspired by the wonderful work and publications by Prof Terry Lyons and his team at the University of Oxford."* The introduction of signatures, combined with the considerable experience Jin and his team had in the development of mobile phone apps, led them to develop a new version of their gPen handwriting recognition app.

Jin demonstrated (again) the benefits of using signatures to represent the features of the input finger strokes in a paper presented at the IEEE 13th International Conference on Document Analysis and Recognition (ICDAR) in August 2015. Along with Weixing Yang, Jin visited the University of Oxford, also in August 2015, in order to start a collaboration with Lyons and Hao Ni, a PDRA employed on Lyons' ERC grant. Subsequently, Yang and another researcher from SCUT visited the University of Oxford at the beginning of 2016 for 3 months, and Lyons visited SCUT twice. This collaboration led to further improvements in Jin's handwriting recognition software (as well as the joint publications [5,6] described in Section 2).

The impact from the University of Oxford's research into Rough Paths has been achieved in two stages:

- Signatures were incorporated into SCUT's free gPen handwriting recognition app, that has been subsequently downloaded by over 1,000,000 users
- the licensing of SCUT's software to Sogou, who have incorporated it into their market-leading Mobile Keyboard for the input of Chinese characters on smartphones, with 75,000,000 users estimated to use the SCUT-derived software each day in China.

Impact part 1: gPen app

Prior to the collaboration with Oxford, Prof Jin's research group already had considerable experience with Chinese handwriting recognition and had an existing mobile phone keyboard app called gPen [C], with versions 1 and 2 released in 2011, and version 3 in 2013. The incorporation of signatures as a key pre-processing step in the version 4, released in 2014, significantly improved the accuracy of the app and enabled character recognition in real time, and additional performance improvements from the collaboration with the University of Oxford were incorporated into version 4.3. As Jin [D] explains: "*This new technology allowed us to develop a fast and compact mobile phone app gPen for IPhone, and Android. Version 4.0 of our software, released in October 2014 was the first mobile phone app to use signatures and neural nets for online Chinese handwriting recognition. Extensive tests showed it to be state-of-the-art. When compared with the other main competitors it was clearly the most accurate, and the tests also showed that the use of signatures was an important part of this success."* In the interview

below, Jin states that version 4.0 and the subsequent versions were downloaded over 1,000,000 times for Android phones.

Left: image of gPen app being used to enter a Chinese character

Right: Sogou Mobile Keyboard handwriting module acknowledgement of SCUT core software [F].

Impact part 2: Sogou Mobile Keyboard

In 2015, Jin's team developed an open source testing tool to objectively evaluate the 6 most popular handwriting input methods then available, including the handwriting recognition software of Sogou. This showed that gPen had the best recognition accuracy on different test sets, and also again demonstrated the importance of using signature information. This led to Sogou approaching SCUT to license their software. Unfortunately, the licensing deal between SCUT and Sogou prohibits Jin from writing about it officially, but the story is captured in an interview given by Jin in July 2020 (edited Google Translation [E]):

[Interviewer] "*From 2015 to 2019, the handwriting setting copyright notice column of the Android version of Sogou mobile input method shows that the technical support is provided by South China University of Technology. Can you share your experience with us?"*

[Jin] "*After we added some data augmentation and preprocessing techniques, we made a recognition effect far superior to traditional methods. […] We compressed and accelerated the model, transplanted it on the mobile phone, and realized the* ***first deep learning-based handwritten Chinese character recognition method on the mobile phone.*** *In 2014, we released this handwriting recognition engine on the Google market, and it has been downloaded more than 1 million* [1,000,000] *times. Once, a Sogou researcher saw our app and evaluated it. We not only have a high recognition rate, but also make the model small and fast. On the mobile phone side at that time, it took about 20ms to complete the entire process of processing a character recognition without a GPU. On the CPU side of the server, it was about 4~6ms. This speed was amazing. The CNN* [convolutional neural net] *model that supports more than 10,000 types of characters is less than 3MB in size. Therefore, under comprehensive consideration, Sogou chose to cooperate with us."*

In 2015, the software in gPen was licensed to Sogou to improve the marketability of their Mobile Keyboard software package by incorporating the gPen methodology and software for handwritten character recognition in place of their own software (which had been shown to be inferior to gPen). The initial software, based on gPen 4.2, was transferred to Sogou at the end of 2015. SCUT continued to develop and update gPen, releasing version 4.3 in May 2016 and a final version 4.3.1 in February 2017 [C].

Although the terms of the licensing deal prevent Prof Jin from revealing most of the details, as mentioned in the interview [E] it included an undertaking from Sogou to publicly confirm, from 2015 to 2019, the use of SCUT's software within the app in the Settings page for the handwriting input module (see the screenshot of the app on the previous page). According to Google Translate, the acknowledgement says "*Handwriting core technology provided by South China University of Technology*" [F].

The Statista website estimates that there were approximately 750,000,000 smartphone users in China in 2019 [G] and, at the end of 2019, Sogou's Mobile Keyboard had over 450,000,000 daily active users [H]. According to the Google Translation of a 2019 survey of mobile phone users by one of China's leading media data analytics companies [I], 61.8% of users prefer a Pinyin interface (either "Jiugongge" or full keyboard), 16.8% prefer handwriting input, 10.0% prefer voice input, and the remainder prefer a variety of other alternatives. The use of handwriting input is also anecdotally described in a Chinese blog article from April 2020 [J], the Google Translation of which says: "*No one writes by hand anymore? But in fact, it's not* [the case]*! With the increasing size of smartphone screens, in addition to pinyin and stroke input, the space available for handwriting input to stretch out also expands. According to the March information of China Internet Network Information Center and Sogou Input Method, as of June 2019, the number of Internet users in my country reached 854 million* [854,000,000], *of which more than 100 million* [100,000,000] *people use handwriting daily, mainly middle-aged and elderly people over 40 years old and small town residents, and handwriting input is an important tool for this part of the user group to embrace the Internet.*"

Based on 16.8% of mobile phone users preferring handwriting input, approximately 75,000,000 people are using Sogou's handwriting module to interact effectively with their mobile devices on a daily basis, benefitting from SCUT's technology that utilises the mathematical ideas of Rough Path signatures developed at the University of Oxford to represent the key features of their handwritten input.

5. Sources to corroborate the impact

[A] Wikipedia entry for Sogou detailing its products (accessed 22 December 2020): https://en.wikipedia.org/wiki/Sogou

[B] KrASIA technology website article on Tencent acquisition of Sogou, 4 August 2020 (accessed 6 December 2020): https://kr-asia.com/why-is-tencent-making-a-move-to-buy-search-engine-sogou

[C] gPen website (accessed 28 November 2020): https://www.appbrain.com/app/gpen-ime繁體版手寫輸入法/net.hciilab.scutgPen.IME

[D] Letter from Professor Lianwen Jin, December 2020

[E] Interview with Professor Lianwen Jin on the Chinese CSDN technology website, 9 July 2020 (accessed 28 November 2020): https://blog.csdn.net/bevison/article/details/107329113 (Chinese webpage; original and Google Translate version provided in PDF source)

[F] Screenshot of Settings page of Sogou handwriting module (accessed 28 November 2020): https://5b0988e595225.cdn.sohucs.com/images/20190506/09e724aa0a21459caefe43774458bdc7.jpeg (Chinese webpage; original and Google Translate version provided in PDF source)

[G] Statista website statistics on smartphone usage in China, 24 November 2020 (accessed 22 December 2020): https://www.statista.com/statistics/430749/china-smartphone-shipments-vendor-market-share/

[H] China Internet Watch technology website article on use of Sogou Mobile Keyboard, 9 March 2020 (accessed 6 December 2020): https://www.chinainternetwatch.com/30365/sogou-q4-2019/

[I] iiMedia Research media analytics website article on Chinese mobile phone input methods, 8 January 2019 (accessed 21 December 2020): https://www.iimedia.cn/c400/63359.html (Chinese webpage; original and Google Translate version provided in PDF source)

[J] Zhihu website – Chinese blog article on use of Sogou's handwriting input, 20 April 2020 (accessed 22 December 2020): https://zhuanlan.zhihu.com/p/133834594 (Chinese webpage; original and Google Translate version provided in PDF source)