Institution: University of Leicester

Unit of Assessment: UoA 10

Title of case study: Novel Concentration of Measure theorems enabling high-accuracy technologies for smart video analytics

Period when the underpinning research was undertaken: 2014-2021

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:
Ivan Y. Tyukin	Professor of Applied Mathematics	Tyukin: from 2007 until present
Alexander N. Gorban	Professor of Applied Mathematics	Gorban: from 2004 until present

Period when the claimed impact occurred: 2015 - 2021

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

1. Summary of the impact

High-Tech industry produce Artificial Intelligence systems assisting human decision-making including security and safety-critical applications. Market-leaders ARM (revenue GBP1.5B as of 2017, 22.9B chips shipped as of 2018), designs and licences hardware and software intellectual property. Its technology reaches to 70% of the global population. ARM developed a new processor for robust, affordable hardware, suitable for scalable object detection which has been enabled by algorithms stemming from research at the University of Leicester. The impact can be expressed in terms of **economic** and increased **awareness and understanding**. The reach of the impact is global through world-wide sales of processors using the underpinning algorithms and the significance is that these algorithms are essential to the performance and competitiveness of the devices. ARM processors are used as the main CPU for most mobile phones, including Apple, HTC, Nokia, PDAs and handhelds, like the Apple iPod and iPad, Game consoles, like Nintendo Switch, as well as many other applications, including GPS navigation devices, digital cameras, digital televisions, network devices and storage.

2. Underpinning research

The work emerged as a direct consequence of a series of industrial projects and initiatives at the department of Mathematics at the University of Leicester. The idea of developing an innovative electronic device enabling *low-cost access to computer vision* was seeded by I. Tyukin, A.N. Gorban and I. Romanenko (Apical Ltd) in 2012. The idea was to produce a device (a chip) costing under GBP10; consuming less than 1 Watt of energy and capable of object detections in high-definition (full HD) live video streams at rates of 30 frames per second. This resulted in a string of industrial, Innovate UK, and ERDF projects [**G1**-**G3**].

The goal was to deliver the highest-possible levels of accuracy and efficiency at the smallest costs possible. To ensure high spatial accuracy and competitiveness of the product, Apical specified an error rate of less than 1 in 12M false alarms whilst achieving the highest possible detection rate.

The solution was a two-stage algorithm; stage 1 used standard filtering approaches to remove the bulk of true negative proposals. Stage 2 fine-tunes the core algorithm. This required a deeper understanding of the geometry of the high-dimensional decisional (4000 dimensions) space of the algorithm. In order to guarantee the specified performance rates Tyukin and Gorban developed a new mathematical framework (theorems and algorithms) for quantifiable improvement of accuracy in existing (legacy) AI systems whose decision-making space is high-dimensional. The new algorithms have been motivated by and are based on stochastic separation theorems [**R2**,**R5**,**R6**], a novel concentration of measure phenomenon enabling the solution to the underlying theoretical challenge.

The classical concentration of measure theorems state that independently identically distributed random points are concentrated in a thin layer near a surface (a sphere or equators of a sphere, an average or median-level set of energy or another Lipschitz function, etc.). The new stochastic separation theorems [**R5**] describe the thin structure of these thin layers: the random points are not only concentrated in a thin layer but, with probability close to one, are all linearly separable from the rest of the set, even for exponentially large random sets. The results generalize to separability of multiple points, due to their near-orthogonality [**R6**,**R1**,**R3**]. The guaranteed possibility of linear separation in high-dimensional spaces for broad classes of realistic and uncertain distributions is at the core of the new algorithms. The linear functionals for separation of points can be selected in the form of the linear Fisher's discriminant [**R1**,**R3**,**R4**], constructed using a non-iterative (one-shot) procedure. The theory has been tested in real-life object detection case studies [**R1**,**R3**] and successful industrial applications.

In particular, the algorithms enabled Apical to create a novel computer vision algorithm capable of 12M image assessments per second and delivering unprecedented levels of false positive errors, 0.0001%, whilst producing market-leading rates of object detection. The chip, released in 2018, costs USD10 and consumes less than 1W of power and is suitable for a broad spectrum of cameras and lenses, including wide-angled. For comparison, dedicated novel devices released in 2019 such as Nvidia Jetson Nano and Google's Edge TPU consume 10W and 2W, respectively. An average tablet: 15W, a laptop computer: 50W-100W; a desktop: 80W-250W; and a comparable GPU workstation: 1000W.

The solutions, based on the underpinning research, were patented by Apical/ARM ([**P1**,**P2**]), and the final product licensed to Ingenic Semiconductors (T01 professional video analysis AI coprocessor).

3. References to the research

[**R1**] Tyukin, A.N. Gorban, S. Green, D. Prokhorov. Fast Construction of Correcting Ensembles for Legacy Artificial Intelligence Systems: Algorithms and a Case Study. Information Sciences, 2018. https://arxiv.org/abs/1810.05593.

[**R2**] A.N. Gorban, I. Tyukin, I. Romanenko. The blessing of dimensionality: Separation theorems in thermodynamic limit. In Proceedings of the 2nd IFAC Workshop on Thermodynamic Foundations of Mathematical Systems Theory, Spain, 28 – 30 September, 2016, Volume 49, issue 24, pages 64-69.DOI:

http://dx.doi.org/10.1016/j.ifacol.2016.10.755
[**R3**] I.Tyukin, A.N. Gorban, K. Sofeikov, I. Romanenko. Knowledge Transfer Between Artificial Intelligence Systems. Frontiers in Neurorobotics, 2018. doi:10.3389/fnbot.2018.00049.
[**R4**] A.N. Gorban, I. Tyukin. Blessing of dimensionality: mathematical foundations of the statistical physics of data. Philosophical Transactions of the Royal Society A 376: 20170237, 2018. doi:10.1098/rsta.2017.0237.
[**R5**] A.N. Gorban, I.Y. Tyukin. Stochastic Separation Theorems. Neural Networks, 94, 255-259, 2017. doi:10.1016/j.neunet.2017.07.014.
[**R6**] A.N. Gorban, I. Tyukin, D. Prokhorov, K. Sofeikov. Approximation with random bases: Pro et contra. Information Sciences, 324-325, 129-145, 2016.

Grants:

[**G1**] Industrial PhD project (2013-17) with Apical Ltd (GBP93,000); project aim 'Image processing methods based on analysis of visual scenes' (PI I. Tyukin)
[**G2**] Partnerships in Knowledge Transfer project with Apical Ltd (2013–14) funded by the ERDF (GBP32,750); project aim: 'To develop object identification and tracking algorithms for image processing tools'. (PI I. Tyukin, CoI A.N. Gorban)
[**G3**] Innovate UK Knowledge Transfer Partnership (2015-17) with Apical Ltd (GBP179,135); project aim: 'To develop a novel visual intelligence technology for efficient image processing, object detection, recognition and tracking, implemented in a System On Chip'. (PI Dr Tyukin, CoI A.N. Gorban)
[**G4**] Knowledge Transfer Partnership (2017-19) with VMS Ltd (GBP206,176); project aim: 'To develop leading edge convergent low-cost, power-efficient security systems capable of real-time facial recognition.' (PI Dr Tyukin, CoI A.N. Gorban)

Patents:

[**P1**] Patent 1. I. Romanenko, I. Tyukin, A.N. Gorban, K. Sofeikov. US Patent number c. Method of Image Processing (August 2018)
[**P2**] Patent 2.I. Romanenko, A.N. Gorban, I. Tyukin. US Patent number US10489634B2. Image Processing. (November 2019)

4. Details of the impact

Economic Impact

As a result of this multi-funded collaborative programme, Apical Ltd produced a prototype of the new device in 2016. Object detection algorithms in this prototype have been underpinned by fundamental research which has been later published in a series of papers [**R1**]-[**R6**] which included joint work with industrial collaborators [**R2**, **R3**].

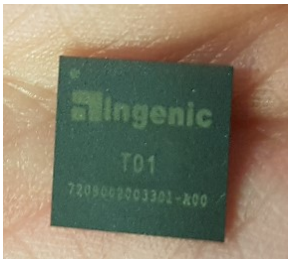

Fig. 1. Ingenic T01 video analysis AI coprocessor and Centrica Hive View Camera

In May 2016 Apical Ltd was acquired by ARM for USD350M, with the IPs for this technology (including the blueprints of the hardware and the object detection models). ARM then licensed the technology to Ingenic Semiconductors and Foxconn. Foxconn is the World's largest contract electronics manufacturer [**E5**].

This led to the production of the T01 Spirit Professional video analysis AI coprocessor. The coprocessor is a core element of Centrica's innovative Hive Smart camera, which can detect a presence of a person within a room helping to discriminate between alarms raised by pets which is not the case in cameras with generic motion sensors. The smart camera went on global market sale in January 2018 and in 2019 Centrica reported "*around 1.8 million customers now use Hive connected home products that can be controlled with just a tap on the app – from smart thermostats, plugs, lights and cameras, to contact and motion sensors*" [**E9**].

Through the project, ARM acquired and built new expertise and capabilities in Machine Learning and Computer Vision [**E4**]. This directly impacted ARM's ability to innovate new technologies "*that give increased performance and accuracy versus existing products*" [**E4**]. ARM is a leading developer of computational architectures and Intellectual Properties (IP) and is the keystone of the world's largest computer ecosystem. *"With more than 125 billion devices containing ARM-based chips, our architecture empowers innovation in multiple markets enabling partner innovation. ARM's IPs feature in 90% of embedded devices globally*." [**E5**]

"*The research at the University of Leicester has underpinned the contribution to the development of the prototype System-on-Chip IP for a novel robust, high-throughput, accurate, and low-power and low-cost solution to the challenge of object detection in live video streams. …. The research also underpinned the development of ARM Object Detection Processor IPs*." [**E5**]. As a result two patents have now been granted [US 10062013B2, US10489634B2].

ARM Object detection Processor IPs underpin ARM's Project Trillium heterogeneous framework combining Cortex CPUs (100B chips as of 2017 [**E10**]), Mali GPUs (**6.8% of Global mobile phones** including Galaxy S8 and S9 and out of about 5.5B mobile phones [**E8**]), and Ethos NPUs (announced in October 2019) to deliver advanced machine learning (ML) user cases [**E7**]. As a further evidence of economic impact, ARM created five graduate positions: "*As a result of our collaboration we now employ five postgraduate students from the Department of Mathematics, University of Leicester and are co-funding one of their joint PhD students*." [**E5**]. All five students have been engaged in collaborative research with Apical which led directly to their job offers.

The project led to a new initiative, large-scale large-volume face recognition for security applications with VMS Ltd, a Scottish-based provider of security solutions with clients ranging from Ministry of Defence, Airports, Power Generation Plants to Museums and Art Galleries. At the centre of the initiative was the novel technology for detecting and processing faces from live video feeds and existing CCTV systems. The research "*has significantly contributed to almost a three-fold increase of the company's turnover from about* [GBP]*2M in 2016 to over* [GBP]*7M in 2019 whilst also improving profitability*", and led to employment of 3 new graduate engineers and supporting 4 new graduate apprenticeships [**E6**].

Understanding and Awareness

The underpinning research which has been developed as a result of collaboration between Apical and UoL and which was subsequently published in [**R1**]-[**R6**] informed Apical Ltd on the fundamental theory enabling the algorithm development [**E1**-**E3**] and gave them "… *insight into how to design future products that give increased performance and accuracy versus existing products.* [**E4**, **E5**]. *"ARM customers want high accuracy object detection, tracking and recognition IP for a wide range of end applications – surveillance, automotive and healthcare to name but three. Non neural network approaches have the advantage of low cost but result in often unacceptable false positive rates. Neural networks have lower false positive rates but at a greatly higher cost. The KTP Project was able to validate that a combination of the two can yield the best of both."* [**E4**]. The research also directly impacted on ARM's capacity and investment plans: *"ARM did not have active research in this field prior to the KTP Project", "…. being actively engaged in research within these fields via KTP, ARM has been able to adjust our investment strategy to take advantage."* [**E4**].

Finally, the research impacted on the preparedness of ARM for future business opportunities: *"ARM Machine Learning Business Unit team have a much greater insight into emerging ML/AI/CV techniques than we did before the KTP project."* [**E4**]

5. Sources to corroborate the impact

[**E1**] A.N. Gorban, I. Tyukin, D. Prokhorov, K. Sofeikov. Approximation with random bases: Pro et contra. Information Sciences, 324-325, 129-145, 2016.
[**E2**] A.N. Gorban, I. Tyukin, I. Romanenko. The blessing of dimensionality: Separation theorems in thermodynamic limit. In Proceedings of the 2nd IFAC Workshop on Thermodynamic Foundations of Mathematical Systems Theory, Spain, 28 – 30 September, 2016, Volume 49, issue 24, pages 64-69.DOI:
[**E3**] Innovate UK KTP (2015-17) with Apical Ltd (£179,135); project aim: 'To develop a novel visual intelligence technology for efficient image processing, object detection, recognition and tracking, implemented in a System On Chip'.
[**E4**] Knowledge Transfer Partnership KTP009890 Final Report. 21st of February 2018.
[**E5**] Letter of Acknowledgement from ARM Ltd
[**E6**] Letter of Acknowledgement from VMS Ltd
[**E7**] https://www.arm.com/products/silicon-ip-cpu/machine-learning/project-trillium
[**E8**] https://deviceatlas.com/blog/most-used-smartphone-gpu
[**E9**] https://www.centrica.com/media/4204/annual-report-and-accounts-2019.pdf pp49
[**E10**] https://community.arm.com/iot/b/blog/posts/enabling-mass-iot-connectivity-as-arm-partners-ship-100-billion-chips