Institution: Loughborough University

Unit of Assessment: UoA 11 - Computer Science & Informatics

Title of case study: Revolutionising Digital Cameras and Displays to Mimic Human Vision with Commercial Success

Period when the underpinning research was undertaken: 2008-2016

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:
Prof Eran Edirisinghe	Professor of Digital Imaging	July 2000 - present

Period when the claimed impact occurred: 2014-2020

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

1. Summary of the impact (indicative maximum 100 words)

Seeing objects as '*real*' is a result of the perceptual capabilities of our eyes. This realism is difficult to reproduce in images captured by cameras and displayed on screens, due to limitations that degrade image quality. Research at Loughborough University contributed to the development of intelligent image/video enhancement algorithms that led to **economic impact** for collaborators Apical Ltd. and ARM UK **via:**

(a) **Improved image quality** captured by cameras – 120M unit licences (£7.5M) sold by Apical and 100M Systems-on-Chips, sold by ARM UK; **and**

(b) **Improved viewer experience** produced via an Assertive Display (AD) – 1B unit licences (£10M) sold by Apical and 0.5B display processors with AD technology sold by ARM.

LU contributed to the generation of the above IP that resulted in the sale of Apical to ARM, for a record $350M in 2016.

2. Underpinning research (indicative maximum 500 words)

A camera can be attributed to a physical model of the human eye. For a camera to capture images that *looks real*, the quality of images captured by a camera's sensor, needs enhancement. Only if this is done in way sensitive to human vision, we will feel that such images look *real*. Further, the human eye has a remarkable ability to view scenes in *High Dynamic Range (HDR)*, i.e. the ability to see detail in very bright and dark environments. Unfortunately, most sensors have limitations of their dynamic range and even if they do not, representing, transmitting, displaying captured HDR images, using existing technologies, are significantly limited. Research led by Prof Edirisinghe (2008-2016) resulted in a portfolio of novel image enhancement and display algorithms that addressed these challenges.

Improving Quality of Images: A lens of a camera can fail to focus all colours to the same point resulting in an annoying effect of *colour-fringing*. In [R1], an algorithm for Correcting Chromatic Aberrations was proposed to remove such artefacts. In [R2], an approach to removing noise in images/video was proposed that results in clear, noise free images/video. We proposed a novel, block-matching/optical-flow based, spatio-temporal algorithm that can remove noise, in images. A novel colour management system for cameras, robust to coping with sensor-to-sensor variations and able to compensate for different illuminants and reproduce pleasant colours (cool/warm) was proposed in [R3]. An algorithm that allows effective capturing of images with both high and low light areas (multi-exposure) and helps clearly focus on objects at different depths in an image (multi-focus) was proposed in [R4]. A unique contribution of the approach was its ability to deal with camera shake during image

capture and remove *ghosting* that result from moving objects. Overarching and unique aspects of the designs of all above contributions is processing pixels as captured by a camera sensor (i.e. raw-pixels), designs that are sensitive to sensor properties, mutual compatibility, computational simplicity and hardware readiness.

Improving Quality of Displays: LU research created novel knowledge in understanding how to effectively use a mobile handset's Ambient-Light-Sensor (ALS) output to derive both the ambient illumination incident on a screen and its backlight that impacts on a user's ability to view content of an image displayed on a screen, with sufficient clarity. The research helped in understanding the operational limitations of the ALS, e.g. limited angle of sensitivity and latency and thus how to improve accurately predicting illumination on a mobile handset screen. LU research also developed a novel solution for HDR video representation, coding and display using legacy Standard Dynamic Range technology that effectively used the ALS to control the Apical's award winning, flagship tone mapping operator, Iridix™ [R5]. LU research further investigated the possibility of using multiple sensors within a mobile device to predict a phone user's intent / phone usage and accordingly model the ambient illumination of a screen, thus optimising the ALS usage and hence saving vital battery power [R6].

3. References to the research (indicative maximum of six references)

R1. Lluis-Gomez, A and **Edirisinghe, EA** (2012) Chromatic aberration correction in RAW domain for image quality enhancement in image sensor processors, *Proc. of 2012 IEEE 8th Int. Conf. on Intelligent Computer Commun. and Process., ICCP 2012*, pp.241-244, DOI: 10.1109/ICCP.2012.6356192

R2. Romanenko, IV, **Edirisinghe, EA**, Larkin, D (2012) Block matching noise reduction method for photographic images, applied in bayer RAW domain, optimized for real-time implementation, *Proceedings of SPIE - The International Society for Optical Engineering*, 8437, ISSN: 0277-786X. DOI: 10.1117/12.922791.

R3. Lluis-Gomez, AL, **Edirisinghe, EA**, IEEE, (2014) A Novel Colour Management System for Image Signal Processors in Commercial Digital Cameras, Proc. of the IEEE International Conference in Consumer Electronics (ICCE), 2014, Las Vegas, NV, USA, pp.43-46. DOI**:** 10.1109/ICCE.2014.6775900

R4. Romanenko, IV, Lluis-Gomez, A, **Edirisinghe, EA**, IEEE, (2014) Image Matching in Bayer RAW Domain to Remove Ghosting in Multi-Exposure Image Fusion, Proc. of the IEEE International Conference in Consumer Electronics (ICCE), 2014, Las Vegas, NV, USA, pp.39-40. DOI**:** 10.1109/ICCE.2014.6775898

R5. Léonce, A, Hsu, TI, Wickramanayake, DS, **Edirisinghe, EA** (2012) High Dynamic Range video transmission & display using standard dynamic range technologies, *Proceedings of SPIE Vol.* 8436, ISSN: 0277-786X, SPIE Photonics Europe, Brussels, Belgium, DOI: 10.1117/12.922851.

R6. Al-Marhoubi, A, Saravi, S, **Edirisinghe, E**, Bez, HE (2015) Illumination modelling of a mobile device environment for effective use in driving mobile apps. Proc. of the SPIE Vol. 9481, 94810R, SPIE Sensing Tech. & App.: Materials, Sys., Devices and App. II, Baltimore, MD, USA, DOI: 10.1117/12.2177087.

The research was funded by competitively-awarded grants: **1**: AllCast R&D Grant - TS/H002243/1 (EPSRC/TSB, £ 162,194, 2008-12), **2**: QPipe KTP - KTP7841 (TSB, £ 121,325, 2010-12), **3**: AllCast Extension KTP - KTP8873 (TSB, £ 103,000, 2012-14), **4**: iModel KTP - KTP1005752 (TSB, £ 93,000, 2014-15). All conference papers were peer reviewed with an average acceptance rate of below 30%.

4. Details of the impact (indicative maximum 750 words)

Loughborough-based SME **Apical Ltd. was already a global leader in imaging and embedded computer vision technology** [S2] before it was acquired by ARM in 2016. Apical's "products were used in more than 1.5 billion smartphones and approximately 300 million other consumer/industrial devices" [S2, S5]. Apical won a Queens Award for Innovation

[S1] and in 2015 was recognised in *The Sunday Times* Tech Track 100 fastest-growing UK technology companies [S2]. In 2016, Apical was acquired by ARM, a company that is globally market dominant for processors in mobile phones, tablet computers, automotive and industrial systems and for systems-on-chips (SoC) in smart TVs [S2, S3].

LU-Apical's collaboration was formally recognised by LU in awarding the partnership with the prestigious *Loughborough University Enterprise Award for Knowledge Transfer*, in both 2013 and 2014. Announcing Apical's outstanding success at the time of its sale in 2016, the contribution of LU research to Apical's success was recognised by Innovate UK:

> *"Apical has worked on a number of knowledge transfer partnerships with Loughborough University… over the last six years. The work has covered a range of areas including image signal processors, high dynamic range (HDR) video, handset displays that adapt to changes in light levels …"* [S5]

LU research contributed to two Apical products, ISPv5 (version-5 of its ISP), i.e. an Image Signal Processor (ISP) that consists of a number of image enhancement functional blocks, which work together to create a superior quality image and Apical's Assertive Display (AD) technology, that enables a display to adjust its display parameters automatically, depending on the illumination of the environment and image content. Apical's ISPv5 and AD technology launched in 2014/15, created significant new revenue to Apical and enabled ARM to include these cutting edge new technologies, within their popular processors, serving the digital camera and display technology sectors, resulting in significant reach and scope of their products.

The collaboration led to two key impacts:

(a) Improved image quality captured by digital cameras - 120M unit licences sold by Apical Ltd. generated £7.5M, and 100M Systems-on-Chips sold by ARM UK

LU's research contributions to improving the quality of images were key to the design and development of Apical's ISP technology, especially the highly successful ISPv5 that was commercially launched in early 2015. LU's contributions to ISP technology and its impact on Apical was acknowledged by: Apical's former, Head of Image Quality (2014-2016) [S3] and by its former CEO [S1] as:

> *"These contributions made ISPv5 a global success in its ability to reproduce superior image from digital cameras, mimicking the capabilities of a healthy human visual system." [S3]*

> "*By 2016, more than 80% of the world's security cameras were based on Apical's ISPv5, which was the product of R&D to which these projects made a contribution. As a result, the company was able to grow its ISP product development and support team by 10 full time staff, and to achieve design wins in new markets, specifically automotive, with customers including Renesas and Tesla. As a result of the new market access, ISPv5 was able to add GBP5M in revenue as compared to ISPv4, corresponding to a total unit volume of in excess of 80M units per year from 2016 onwards"* [S1].

ISPv5 was launched in early 2015 and by summer 2016, 120 million unit licenses had been sold generating a revenue of £7.5 million to Apical. [S2]. As Apical earned its revenue by selling Intellectual Property (IP), this revenue was generated through licensing the ISPv5 IP not only to digital camera manufacturers such as *Huawei* (biggest player in security camera market) and *Polycom* (biggest player in videoconferencing products) and chipset makers (*Maxim* and *Hisilicon*), but also through licencing directly to the Original Equipment Manufacturers (OEMs) such as world's top three Smartphone brands, (including *Samsung, Huawei*) and to world's top handheld camera brand (*Sony*) [S3].

Since ARM's acquisition of Apical, ARM re-purposed, re-branded and launched Apical's ISP as its Mali ISP range. ARM's Technical Director Imaging, comments:

> *"All major image quality enhancement modules of Apical ISPv5 that had a huge global licensing portfolio by 2016 at the time of Apical's acquisition by arm, subsequently became the image enhancement backbone of arm's globally adopted Mali ISP range."* [S3].

Mali C-71 ISP, focused on the Automatic Driver Assistance Systems and was launched in 2017 [S3,S7]. Steve Steele, of ARM's IVG, was quoted making the statement, "*We do feel, genuinely, that our ISP is the best that's available*" [S8]. By 2019 Mali C-71 ISP had been licensed to top fully-electric car manufacturer TESLA and a number of other high-end car manufacturers, including VW. ARM launched its Mali C-52 and Mali C-32 ISPs in 2019, focused on embedded applications such as security cameras, drones, and home assistants [S3,S9]. The C52 covers the whole spectrum, while the C32 is for customers more concerned about power and area budgets. Mali C-32 has been licensed to the top global drone manufacturers. Since its launch the ARM Mali ISP range has become globally popular and its impact has been far reaching, as stated by Technical Director, ARM UK:

> *"I can confirm that to-date over 100 million SoCs (System-on-Chips) with arm Mali ISPs have been shipped worldwide, since Apical's acquisition in 2016. These designs are based on the large number of novel, unique and highly practically functional, image enhancement algorithms developed as a part of research conducted within your research team between 2010-2015"* [S3].

LU research was further exploited by Apical to create the "Real-Time HDR" feature (algorithm and hardware IP) [S5] of the Samsung Galaxy smartphone, first introduced in Samsung Galaxy v.5 (in 2014) and used up to v.8. It enabled the capture of HDR images and videos, and with no ghosting artefacts during image fusion, a world's first. At the time of Apical's sale in summer 2016, the total revenue generated from IP sales of this product to Apical was estimated at £2M [S2]. The significance of this impact was reported by former CTO, Apical Ltd.:

> *"Due to this unique feature Samsung Galaxy phones (versions 5-8) kept a leading position among smartphone, in terms of picture quality"* [S2].

Commenting on the Apical ISP technology that continues to create significant impact globally, Apical's former Head of Image Quality and ARM's Technical Director, Imaging, reported that:

> *"This technology re-defined the image quality expectations of consumers and was fundamental to initiating a push towards the photorealism of visual digital content worldwide*" [S3].

(b) Improved viewer experience via an Assertive Display (AD) - 1B unit licences sold by Apical Ltd generated £10M, and 0.5B display processors with AD technology sold by ARM UK

Our research on *Improving Quality of Displays* automated the use of Apical's flagship Iridix™ tone-mapping technology, for the dynamic adaptation of an image for displaying in given viewing conditions, i.e. in the presence of varying ambient light (for e.g. viewing in bright sunlight and in dark rooms). This resulted in the launch of Apical's Assertive Display (AD) technology in 2014. LU contributed to the development of AD technology by developing an intelligent Calibration Tool for smart phones, that accurately calibrated the Assertive Display, depending on various sensor data, ambient illumination, reflectivity of the surface of the screen, etc [S4]. This resulted in a reliable and automated calibration process for AD that is more responsive to a mobile phone's environment, battery power, usage, and hardware [S6, S10]. Apical's AD technology directly contributed to the displays of three of the world's top

mobile phone brands and to displays of many other leading mobile, TV and laptop/desktop manufacturers. At the time of Apical's sale to ARM in 2016, the unit sales had reached 1 billion units, generating an estimated £10M in revenue [S2]. Apical's former CEO acknowledged LU's contributions:

> *"Your group studied algorithms to help overcome the limitations of the ambient light sensors typically employed in smartphones, using advanced sampling techniques. This work helped to support the ongoing development of a product which contributed approximately GBP10M in revenues to Apical in 2016"* [S1].

Since Apical's acquisition ARM has continued to maintain the stand-alone AssertiveDisplay™ licensing contracts of Apical, but in addition has incorporated the technology within the ARM Display Processor, which has been licensed to mobile, laptop and TV markets, with additional sales exceeding 500M units by 2020 [S4]. The Loughborough team's contributions to the AD technology have been acknowledged by former Senior Product Manager, AssertiveDisplay™ ARM:

> *"With the best-in-class performance of its Iridix™ local tone mapping engine, it has defined the reference quality level for tone-mapping (i.e.dynamic range management, sunlight visibility) applications. The collaboration with LU has been extremely important during the development and evolution phases of AD at Apical Ltd. and has contributed significantly to the success of the AssertiveDisplay™ technology*" [S4].

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1 Letter from the former CEO and founder of Apical Ltd, Dr Michael Tusch, 11th January 2021.

S2 Letter from the former CTO, co-founder of Apical Ltd., former Senior Technical Director of Imaging, ARM Holdings UK, Dr Slava Chesnokov, 19th November 2020.

S3 Letter from Technical Director, Imaging, ARM UK, Dr Alexis Lluis-Gomez, 5th December 2020.

S4 Letter from the former Product Manager (Assertive Display), Apical Ltd. former Senior Product Manager (Assertive Display), ARM UK, Mr. Sinan Yalcin, 17th November 2020.

S5 Innovate UK News, 26th May 2016, "Apical: imaging and computer vision firm bought for $350 million".

S6 Judd Heape, Senior Director, Marketing in IVG at ARM talks about Apical that was acquired by ARM in May 2016, enabling Computer Vision in a new area on the SoC, already shipped with over 500 million ARM Processors. – 27th October 2016.

S7 Forbes article, 25th April 2017, "ARM introduces first ISP since Apical Acquisition, targeted at Advanced Driver Assistance Systems".

S8 The Verge article, 27th April 2017, "ARM designed an image signal processor and that's a big deal".

S9 WikiChip Fuse news article, 3rd Jan 2019, "ARM Announces the Mali-C52 and Mali-C32 ISPs for Intelligent Vision Devices", David Schor.

S10 XDA Developers article, 2nd Nov 2017", ARM Announces the Mali-D71 and Assertive Display 5 for Better VR Performance and HDR Content", Idrees Patel.