Institution: Loughborough University

Unit of Assessment: B11 Computer Science and Informatics

Title of case study: Image Enhancement Pipelines that Allow Digital Images to be Viewed as Seen by Human Eyes

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

This case study presents two imaging pipelines of Apical Ltd: an Image Signal Processor (ISP) capable of optimising the visual quality of images captured by a digital camera sensor and a Video Signal Processor (VSP) capable of efficiently representing, delivering and displaying High Dynamic Range (HDR) video. The impact created includes:

1. Economic impact – 5 million ISP unit sales in 2013, generating a revenue of £750K

2. A new Product Range – 'Assertive Content' based on VSP technology

The underpinning research for the above developments was carried out at Loughborough University since 2004.

2. Underpinning research (indicative maximum 500 words)

A digital imaging pipeline is an integrated collection of image enhancement, processing and coding algorithms that result in the improvement of the quality of experience in viewing an image or video that has been captured by an imaging sensor.

Since 2000 researchers of the Digital Imaging Research Lab (DIRL), Loughborough University (LU) have focussed their research on image/video representation, coding, enhancement and processing. More recently research has been directed at developing novel image/video enhancement algorithms, High Dynamic Range (HDR) image/video coding algorithms and pipelines. Of particular interest has been addressing open research problems that prevent such algorithms being used in practical applications/systems. In addition the specific challenges addressed by DIRL's research include the computational simplification of algorithms, designing algorithms that are capable of working optimally under resource constraints (bandwidth, memory, CPU and battery usage) and maintaining hardware compatibility.

A single algorithm that can address both multi-focus and multi-exposure image fusion, prior to the introduction of compression artefacts was proposed in **[3.1]**. This work was extended to fusing images in the wavelet transform domain using an image registration algorithm that can compensate for multi-dimensional camera shake **[3.6]**. The use of perceptual colour spaces in HDR image compression was proposed in **[3.3]**. A spatio-temporal noise reduction method in the Bayer raw domain was presented in **[3.4]** which was optimised real-time implementation. A chromatic aberration correction algorithm in raw image domain was presented in **[3.5]**. Further algorithms for automatic white balancing and colour constancy in Bayer raw domain, a barrel and pinching distortion removal algorithm and a fisheye correction algorithm have been developed.

A novel approach to HDR video transmission and display using Standard Dynamic Range (SDR) technologies was proposed in **[3.2]**. A unique feature of this contribution is that it is able to use ambient and back lighting levels of the display to seamlessly adjust the viewer's quality of experience, when the video is displayed on a SDR display. This work was funded by the EPSRC **[G3.2]** as a part of a TSB Research & Development grant in collaboration with Apical Ltd and BskyB.

The DIRL's underpinning research in maximising the end-to-end quality of MPEG-4 & H26L video coding standards over wired networks **[G3.1]** has been extended and used in the performance optimisation of the above ISP and VSP pipelines, when performing under multiple operational constraints.

Within the TSB funded Knowledge Transfer Partnership (KTP) project, QPipe **[G3.3]**, concluded in November 2012, the KTP Associate Mr Alexis Lluis-Gomez (December 2010 – December 2012) under the supervision of Academic Lead, Prof. Edirisinghe, has led the development of Apical

Ltd.'s market leading ISP v4 and the future ISP v5, underpinned by the DIRL's research described above.

Within the TSB funded, R&D project Allcast **[G3.2]** and the KTP project **[G3.4]**, Dr Dhammike Wickramanayake, (February 2008 – January 2014) under the supervision of Prof. Edirisinghe, has led the design, implementation and the creation of the production prototype of Apical's new product range, 'Assertive Content', focused at application domains of mobile, broadband and broadcast TV service provision.

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

3.1. Zafar, I., Edirisinghe, E.A. and Bez, H.E. (2006) Multi-Exposure & Multi-focus image fusion in transform domain, *Proceedings of the IET International Conference on VIE 2006*, IET Int. Conf. on VIE 2006, 606-611, ISBN 0 86341 671 3/9. DOI: 10.1049/cp:20060600

3.2. **Léonce, A, Wickramanayake, DS, Edirisinghe, EA, Hsu, T-I (2012) High Dynamic Range video transmission & display using standard dynamic range technologies, *Proceedings of SPIE - The International Society for Optical Engineering*, 84361D, ISSN: 0277-786X. DOI: 10.1117/12.922851**

3.3. Dolzhenko, V, Chesnokov, V, **Edirisinghe, EA** (2012) Perceptual colour spaces for high dynamic range image compression, *Proceedings of SPIE - The International Society for Optical Engineering*, 843608, ISSN: 0277-786X. DOI: 10.1117/12.922848

3.4. Romanenko, IV, **Edirisinghe, EA**, Larkin, D (2013) Spatio-temporal noise reduction method optimized for real-time implementation, *Proceedings of SPIE - The International Society for Optical Engineering*, 86550L, ISSN: 0277-786X. DOI: 10.1117/12.2001661

3.5. **Lluis-Gomez, A and Edirisinghe, EA (2012) Chromatic aberration correction in RAW domain for image quality enhancement in image sensor processors, *Proceedings - 2012 IEEE 8th International Conference on Intelligent Computer Communication and Processing, ICCP 2012*, 241-244, DOI: 10.1109/ICCP.2012.6356192**

3.6. **Lluis-Gomez, A, Saravi,S, Edirisinghe, EA (2013) Multi-exposure and multi-focus image fusion with multidimensional camera shake compensation, *Journal of Optical Engineering*, SPIE, 52(10), 102007, DOI: 10.1117/1.OE.52.10.102007**

Note: Publication of the underpinning research carried out by Loughborough University was temporarily put on hold due to commercial reasons and confidentiality agreements. Therefore the majority of the above research articles were published since 2012/13.

Grants that supported the above underpinning research and contributed to knowledge transfer:

G3.1.Grant Title: Maximising the End-to-End quality of the MPEG-4 and the H264L standards

   PI: Prof.C.Grecos, CI's: Prof.E.A.Edirisinghe & Prof.D.Parish, LU

   Grant number: GR/S61997/01, Sponsor: EPSRC

   Period of grant: 01/05/2004 to 31/08/2007, Value: £ 170,599

G3.2. Grant Title: AllCast , PI: Prof. E.A.Edirisinghe, LU

   Grant number: TS/H002243/1, Sponsor: EPSRC

   Period of grant: 01/02/2008 to 31/01/2012, Value: £ 162,194

G3.3. Grant Title: QPipe, PI: Pof. E.A.Edirisinghe, LU

   Grant number: KTP grant 7841, Sponsor: EPSRC, TSB, UK industry

   Period of Grant: 01/12/2010 to 30/11/2012, Value: £ 121,325

G3.4. Grant Title: AllCast extension KTP, PI: Prof. E.A.Edirisinghe, LU

   Grant number: KTP grant 8873, Sponsor: TSB, UK industry

   Period of grant: 01/11/2012-31/01/2014, Value: £ 103,000

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

Pathways to impact

One of Apical's key products is an Image Signal Processor (ISP) [5.2]. Apical is a world leader in this technology and licenses ISP's to all major camera and chip set manufacturers, worldwide.

LU's first contribution to Apical's ISP was to ISPv4, where LU's research on multi exposure and multi focus image fusion algorithms, automatic white balancing algorithms, an automatic colour correction algorithm, a camera anti-shake algorithm and an image de-noising algorithm have all contributed to enhance and optimise the ISP's performance. The research underpinning this work has been carried out at the DIRL, since 2004 [3.1-3.6] but was integrated within the ISPv4, formally, through the Knowledge Transfer Project, QPipe [G3.2].

ISPv4 entered production with two initial licensees: Maxim and Hisilicon, who started shipping the ISP products in early 2013. Subsequently a licensing arrangement with Huawei, one of the biggest players in IP security camera market has led to an increasing proportion of the world's IP security cameras at present using ISP v4. Further, ISPv4 is also the basis for several of Polycom's videoconferencing product ranges. Apical licenses ISPv4 to chipmakers on a unit royalty basis, which is typically 3% of the chip's actual selling price (ASP). In practice, this yields between 10 and 20 pence per unit. The volume of shipments in the first three quarters of 2013 has been 5M units, generating revenue of approximately £750K. Apical expects volumes in 2014 to be high as 20M units and in 2015 to reach 50M units.

Apical is currently finalising the design of the ISPv5, in which some further advances made during the QPipe project [G3.2] (novel chromatic and geometric aberration reduction algorithms) are being included.

Apical's key flagship product is Iridix^{TM}, an image enhancement algorithm that helps one to enjoy digitally captured and processed images as seen by human eyes. Due to algorithmic limitations, its use was limited to consumer devices having small displays, such as mobile phones and digital cameras. The implementations were also hardware due to low speed of alternative software implementations. Within the Allcast project [G3.1], the research conducted within the DIRL integrated Iridix^{TM} within an end-to-end HDR video capture, transmission and display system (the Allcast VSP), that utilises existing Standard Dynamic Range (SDR) technologies and adapts automatically to the ambient illumination and backlight. The new technology enables Iridix^{TM}'s effective use in association with larger displays, broadening its reach to broadband and broadcast TV application domains. Since the completion of [G3.1], within the KTP project [G3.3], LU and Apical have developed the AllCast VSP into a full production prototype, i.e., Apical's new product, 'Assertive Content', with client running under Android OS **[5.1 and 5.2].**

Apical is currently in active discussion with 4 companies regarding commercial licensing and deployment of its 'Assertive Content' technology: [Text removed for publication]

Apical expects initial licensing revenues from the VSP technology within 2014 and additional royalty revenues in excess of £10M over the next 5 years.

Beneficiaries

Apical Ltd. has directly benefitted from the collaborative work with the DIRL, LU, with the latest versions of the ISP and its VSP that resulted from the underpinning research [3.1-3.6] and collaborative projects [G3.1-G3.3].

The secondary beneficiaries include electronic device (mobile phone, tablet PCs, laptops and TVs), chip-set manufacturers and vendors of latest multi-media players. The significance of the image quality enhancements and improved quality-of-experience achievable via the use of Apical's ISP and VSP technologies is proven by the worldwide unit sales of 5 million units within 9 months of commercial exploitation and the profiles of the companies that have signed licensing agreements with Apical for future exploitation.

Close collaboration has led to Apical Ltd employing six of Prof. Edirisinghe's PhD & MSc students [Leonce (PhD 2010-2013), Lluis-Gomez (MSc 2009-2010), Taylor (MSc 2008-2009), Wickramanayake (PhD 2006-2009), Zafar (PhD 2007-2010), Zhang (MSc 2011-2012)] who were

directly involved in knowledge transfer activities during the period 2006-to-date. Further, at present four additional Apical employees (Dolzhenko, Lluis-Gomez, Rabykin, Romanenko) are registered as part-time PhD students supervised by Prof Edirisinghe and contribute to the development of the ISP and VSP technologies [3.3-3.6].

The significance and the success of the knowledge transfer activities between the submitting Unit and Apical Ltd. was formally confirmed in 2013, when the partnership won the prestigious '2013 Loughborough University Enterprise Award for Knowledge Transfer'. The KTP project Qpipe (G3.3) was awarded an 'outstanding' rating in the final review by the TSB.

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

The following sources of corroboration can be made available at request:

5.1.   Letter from The Chief Executive Officer, Apical Ltd, Suite 343, 162-168 Regent Street, London W1B 5TD.

5.2.   Apical Ltd website, http://www.apical-imaging.com/

5.3.   Altera information, http://www.altera.com/end-markets/industrial/video-surveillance/image-sensor/ind-image-sensor.html

5.4.   PRNewswire article, http://www.prnewswire.com/news-releases/hisenses-new-security-camera-is-based-on-an-innovative-wide-dynamic-range-solution-developed-by-altasens-and-apical-122539123.html

Note: 5.1 is the main source of corroboration. 5.2 is the Apical Ltd.'s website that includes details of Apical's products that incorporates DIRL-LU's underpinning research and details of some third party partnerships. 5.3 and 5.4 are two websites that provides examples of the ISP and VSP commercialisation by Apical.