Institution: University of Westminster

Unit of Assessment: UoA11; Computer Science and Informatics

Title of case study: Balanced Model Truncation (BMT) and its Applications in DSP System Modelling and Computational Complexity Reduction

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

Work undertaken at the Applied DSP and VLSI Research Group since the early/mid nineties, has led to a number of significant contributions underpinning the development and commercial exploitation by industry of power efficient and complexity reduced integrated Digital Signal Processing (***DSP***) systems and products. These developments have paved the way for a new paradigm in the design of complexity reduced electronic systems aiding the emergence of numerous new commercial application areas and products in a diversity of fields. Indeed, these developments continue their currency and applicability in today's electronic products sector and thus shall be at the core of this case study.

2. Underpinning research (indicative maximum 500 words)

- Designing DSP systems that comprise digital filters to meet a given specification is always possible at the expense of high dimensionality and computational complexity (which is often impractical for real-life implementation). Coming up with an equivalent solution that meets the initial specification at a fraction of the computational complexity is now a reality through the novel deployment of the Balanced Model Truncation (***BMT***) approach. The end result is a lean and mean, low computational complexity, low-power, and implementation friendly equivalent.

  At the heart of the findings relating to the impact claimed in this case study is the BMT approach. The BMT approach we used to generate the much simpler implementation friendly equivalent systems drew on the success of the control theory community in developing the technique of balanced model reduction during the 1980s. One of our earliest major papers in this area [1] pushed the dimensionality focus from the very low-order, primarily continuous-time systems, to high-order, high computational complexity, Digital Signal Processing systems. However, we have since taken the applicability, realisation efficiency, and ease of use of this approach to a different dimension with the support of an EPSRC project award. Moreover, a number of industrial-applied research contracts have directly deployed, extended and expanded the applicability and effectiveness of this approach for cutting edge product development.

  The applied research results made possible through the detailed work and discoveries made during the EPSRC-funded investigations and work that followed, has truly proven to be a watershed. This is due to the fact that our works in this area have become prominent standard practices in the field, and they continue in this way today. The simple and humble baseline that was set in [1] mushroomed out to a much enlarged scope of system modelling beyond its roots in simple fixed linear time-invariant filtering. Many major extensions and novel applications and implementations have resulted from our work, and new ones continue to be discovered.
- The design of arbitrarily specified digital filters and systems having real or complex responses was primarily done in the high computational and implementation-complexity Finite Impulse Response (***FIR***) domain. This was due to the ease of design, abundance of design tool and algorithm availability, and their guaranteed stability. On the other hand, the scene for low computational and implementation-complexity Infinite Impulse Response (***IIR***) filters and their design algorithms was, and still continues to be, less attractive. Their main downfall was the unavailability of appropriate design tools/algorithms, lack of ease designing for arbitrary specifications, and most importantly, their inherent stability issues.
- The problem of designing arbitrarily specified IIR filters with ease and guaranteed stability, as well as low computational and implementation-complexity, was tackled and solved with many practical and commercially exploitable applications. Such applications were derived from the work that was undertaken as a result of the EPSRC, Research Grant No GR/J91777, in 1994.
- Work in the commercial exploitation and use of this approach continues today with the most recent being an applied research contract from the European Space Agency in partnership with Astrium UK Ltd. This started in September 2011 ending in September 2013 to deploy BMT derived complexity reduced IIR filters for their DSP engines onboard their commercial communication satellites in order to reduce computational and implementation complexity, and hence power consumption by multiple orders.
- The approach was generalised from merely a humble filter design strategy, to one that could take

a signal or system that was defined by a large time series to a representative, accurate model. This allowed for a recreation of the original time series from a much reduced complexity model which encapsulated all of the characteristics of the original time series, and as a result paved the way for many novel, practical applications for commercial products.

- The initial paper on the subject was published in March 1992, but the bulk of the new and most impacting work was carried out during the lifetime of the EPSRC project, 01 September 1994 through to 28 February 1998, and continues today.
- The key researchers at the time were Izzet Kale (Reader), Gerry Cain (Professor, Head of School), who has left Westminster in the Academic year 2001-2002, Jonathan Mackenzie (EPSRC project post doctoral research fellow (1994-1998)), Richard C. S. Morling (Head of Department) who has retired January 2013, Bartek Beliczynski (Principal Lecturer), who has left Westminster in the Academic year 1993-1994 and J. Huopaniemi and V. Valimaki who were visiting researchers at Westminster and left for Helsinki University of Technology (HUT) in 1995.
- This work started as a purely theoretical algorithmic exercise in deriving an equivalent IIR model for an FIR filter and ended up being a very powerful approach that is capable of solving a plethora of problems in real-life practical systems, holding its currency and popularity to-date.

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

[1]***** Kale I., B. Beliczynski, J. Gryka and G. D. Cain, “FIR filter order reduction: balanced model truncation and Hankel-norm optimal approximation”, *IEE Proc. of- Vis. Image Signal Process.,* vol. 141, no. 3, pp. 168-174, June 1994

[2] Kale, I. and R. C. S. Morling, "An integrated ΣΔ codec for mobile telephone applications", Proc. 38th Midwest Symposium on Circuits and Systems, (MWSCAS), vol. 2, pp. 945-948, Rio de Janeiro, 13-16 August 1995.

[3] Mackenzie, J., I. Kale, G.D. Cain, "Applying balanced model truncation to sound analysis/synthesis models", Proc. International Computer Music Conference, ICMC '95, pp. 400-403, Banff, Canada, 3-7 September 1995.

[4]***** Mackenzie, J., J. Huopaniemi, V. Valimaki and I. Kale, "Low-order modelling of head-related transfer functions using balanced model truncation", IEEE Signal Processing Letters, vol. 4, no. 2, pp. 39-41, February 1997.

[5]***** Ahfir, M., I. Kale, and D. Berkani, “An Alternative Approach to the Balanced Model Truncation Algorithm for Acoustic Minimum-Phase Inverse Filters Order Reduction”, ISRN Signal Processing Journal, Volume 2011 (2011), Article ID 971051, 6 pages, doi:10.5402/2011/971051, web link: http://www.isrn.com/journals/sp/2011/971051/ref/

[.]* Indicator of best quality

GRANT 1:

- *Awarded to.*: Gerry Cain and Izzet Kale
- *Title*: “Extension of Balanced Model Reduction Techniques for Flexible Digital Filter Design”
- *Sponsor:* EPSRC, Research Grant No GR/J91777
- *Period:* 01 September 1994 - 28 February 1998
- *Value:* £121,567

GRANT 2:

- *Awarded to:* Izzet Kale and Richard C. S. Morling
- *Title:* “Efficient Techniques for Onboard Processing”
- *Sponsor:* European Space Agency/Astrium UK Ltd.
- *Period:* 01 November 2011 - 31 October 2012
- *Value:* £92,000

GRANT 3:

- *Awarded to:* Izzet Kale
- *Title:* “Extensions of Efficient Techniques for Onboard Processing”
- *Sponsor:* European Space Agency/Astrium UK Ltd.
- *Period:* 01 April 2013 - 31 September 2013
- *Value:* £42,000

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

- Applied industry-based research for industry's next generation products has been one of the mainstream activities of the Applied DSP and VLSI Research Group at Westminster. Often many of the projects and tasks therein had a large proportion of integrated DSP systems that heavily relied on and were limited by high computational and implementation-complexity digital filters. These had to occupy the least amount of silicon real-estate, operate as fast as possible, and consume the minimum amount of power. This is unfortunately extremely impractical and unfeasible to sustain in real life.

  The research underpinned in this case study has, on most of these products, resolved this requirement-conflict issue. Through orientating these applied research projects, guiding, and furnishing the design and implementation cycles with BMT to maximise the output efficiency (as per the requirements from the distinct specifications), this result was achieved.
- The impact resulted in new reduced computational and implementation-complexity approaches to integrated DSP systems that found and continue to find use in a diversity of products and spheres. These range from mobile phones, to hearing aids, to onboard satellite processing systems, satellite positioning systems to binaural 3D sound systems, and beyond.

  This impact is strongly evidenced by the fact that the real-life applications of the theoretical work that was done and published back in the mid to late nineties is still keeping its currency and finding used in real-world practical systems and products.
- The results of the underpinning research were disseminated to the wider technical and industrial communities in a number of ways finding uses in their products. These were primarily through the use of the open literature publication channels, industrial company based short courses delivered to industry which, in many cases, resulted in applied research and development project contracts for their next generation products. The results and findings of the research was furnished and supported to potential beneficiaries through invited talks, seminars, and word of mouth, which eventually resulted in more funded projects, the most recent of which started in April 2013. *The main influential aspect of the output that attracted commercial as well as academic interest has been the approach's ability to reduce computational and implementation-complexity, and hence, implementation cost without loss of performance.*
- The research and its results detailed in this case study were almost exclusively undertaken at the University of Westminster, and the beneficiaries have mostly come from industry. Exceptions to the contributions were from J. Huopaniemi and V. Valimaki who were at Westminster at the time of the research when they contributed to one strand of the work in the area of Head Related Transfer Functions (***HRTFs***) with their a-prior knowledge of FIR HRTFs and their associated problems. We subsequently solved this problem for them through BMT derived IIRs and published papers with them, one of which is [5]. Consequently, they returned to Helsinki University of Technology and continued in this strand of work and have undertaken applied research consultancy projects for NOKIA. The products resulting from this work are known to have produced superior fidelity and reduced complexity Head Sets which generated multi-million revenues in the binaural sound and headset industry.
- Dialog Semiconductor, and Ericsson Mobile Phones. IIR filters derived using the BMT techniques have found use in the Ericsson 688 and 768 handsets (announced in 1997 and were in use till the early to mid 2000s) delivering low computational and implementation complexity and low power and therefore, extending the battery-life. We can only speculate as to the sheer multi-million/billion revenues that resulted from these sales judging by their popularity at the time.
- Mitel Semiconductor/Zarlink Semiconductor/Starkey Labs, BMT derived IIR filters for their digital hearing aid codec and processors. Their digital hearing aids containing our technology were launched in 2003. This opened up new avenues of opportunity for those hard of hearing,

improving their quality of life through extended battery life as well as allowing them to individually customise their digital hearing instruments. As these hearing aids have been in full production since 2003 we can once again, only speculate as to the multi-million revenues that it generated, as well as the quality of life improvements achieved for those who use them.

- Nokia, through HUT, on BMT derived low complexity IIR HRTFs. This work has found itself in the heart of many of today's 3D binaural headsets used in many gaming and immersive/virtual reality systems. Once again the revenues and improvement of quality of life and superior user experience resulting from the use of this technology can only be speculated on.
- European Space Agency/Astrium, reduced computational and implementation-complexity, low power onboard satellite processing algorithms for communication satellites. Work in this area is now at its maturity and has resulted in a very impressive output that Astrium and the European Space Agency are very impressed with. Indeed, they will be deploying it in their next generation satellites, as well as launching into a new contract with us to look into further application areas. In the space, namely satellite positioning filed the activity also found use in a recent large collaborative EPSRC funded research project with partners from Imperial Collage, UCL and Nottingham University where we were responsible for the software and hardware design implementation and prototyping for the next generation of Global Navigation Satellite Systems.
- The industrial manufacturers/beneficiaries listed above have all benefitted in the same way, namely in being able to integrate computational and implementation-complexity reduced low power devices into their systems on chip.
- The consumers have enjoyed cheaper and lower power, and hence, longer lasting battery life and wider functionality offering products.
- Evidence to support the claims made in this case study can be provided in the form of letters and testimonies form the industrial clients the work was done for.
- The impact occurred 2 to 3 years after the work was carried out and published continuing to date.

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

- EPSRC, Research Grant No GR/J91777, progress reports
- Designs and design documentation from applied research contracts for:
  (a) Dialog Semiconductor on the Ericsson 688 and 768 mobile handsets
  (b) Nokia for the car impulse responses complexity reduction
  (c) Nokia through Helsinki University of Technology, Finland for the HRTFs and related sound and musical instrument synthesis work
  (d) Zarlink Semiconductor for the Starkey Silicon Integrated Hearing Aid filters
  (e) European Space Agency project for ASTRIUM on complexity reduction in onboard satellite digital signal processing engines.
- The following key beneficiaries have provided the University with factual corroborating statements that could be made available to the REF team:
  (a) Zarlink Semiconductor, San Diego, USA
  (b) Dialog Semiconductor, Swindon, UK - Director of Engineering, PMIC development
  (c) Astrium Ltd, Stevenage, UK – Engineering, Payload Equipment (APP4), Processor Product Group, Processing and Timing Product Line Group (APP3)
- The following users / beneficiaries can be contacted by the REF team to corroborate claims:
  (d) Helsinki University of Technology and Aalto University, Finland
  (e) European Space Agency, ESA ESTEC, Noordwijk, Holland