

Impact case study (REF3b)

Institution: University of York
Unit of Assessment: 11, Computer Science and Informatics
Title of case study: RapiTime: Worst-Case Execution Time technology [REDACTED]
1. Summary of the impact (indicative maximum 100 words)

Impact: The underpinning research resulted in an innovative Worst-Case Execution time (WCET) analysis technology now called RapiTime, which was transferred to industry via a spin-out company, Rapita Systems Ltd. The technology enables companies in the aerospace and automotive industries to reduce the time and cost required to obtain confidence in the timing correctness of the systems they develop. The RapiTime technology has global reach having been deployed on major aerospace and automotive projects in the UK, Europe, Brazil, India, China, and the USA. Key customers include leading aerospace companies such as: [TEXT REMOVED FOR PUBLICATION]; as well as major automotive suppliers: [TEXT REMOVED FOR PUBLICATION]. Since 2008, Rapita has won export orders to China worth over [TEXT REMOVED FOR PUBLICATION]. From 2008/9 to 2011/12, the company's annual revenues have more than doubled from [TEXT REMOVED FOR PUBLICATION] to over [TEXT REMOVED FOR PUBLICATION]. As of August 2013, Rapita employs [TEXT REMOVED FOR PUBLICATION] people at its offices in York and Cambridge.

2. Underpinning research (indicative maximum 500 words)
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Context: Determining the longest time that software components can execute on a microprocessor, referred to as the Worst-Case Execution Time (WCET), is a key issue in the development of real-time embedded systems in the aerospace and automotive industries. Here, intermittent timing failures caused by software exceeding its budgeted execution time can lead to operational problems, reliability issues, and in some cases catastrophic consequences. In these applications the WCET of software components needs to be tightly bounded to avoid the need to overprovision hardware in terms of faster, but more costly processors.

Prior to the underpinning research, there were two main approaches to WCET estimation; end-to-end measurement and static analysis. End-to-end measurement techniques insert profiling code into the software. During testing this profiling code records the end-to-end execution time of each invocation of each software component. End-to-end measurement alone typically under-estimates the WCET, and provides little confidence that timing constraints will always be met during operation. Static analysis techniques analyse the software object code and compute the WCET using a model of the timing behaviour of the microprocessor. This is done without running the code. Using static analysis alone has the disadvantage that the computed WCETs depend on the accuracy of the timing model of the processor and its hardware acceleration features.

Underpinning research: During the NextTTA project (1st Jan 2002 to 31st Jan 2004) four members of the Real-Time Systems Research Group (RTSRG) in the Department of Computer Science at the University of York, Guillem Bernat, Antoine Colin, Stefan Petters, and Alan Burns developed a set of hybrid and probabilistic techniques for WCET analysis [1], [2], [3], [4], and [5], now referred to as RapiTime. The RapiTime approach combines static analysis of the structure of the source code with timing measurements taken during testing, which record the execution time of short sub-paths through the code. RapiTime recognises that the best possible model of an advanced microprocessor is the microprocessor itself and therefore uses *online* testing to measure the execution time of short sub-paths in the code. By contrast, *offline* static analysis is the best way to determine the overall structure of the code and the paths through it. Therefore RapiTime uses path analysis techniques to build up a precise model of the overall code structure and determine which combinations of sub-paths form complete and feasible paths through the code. Finally the measurement and path analysis information are combined using statistical methods to compute WCETs in a way that captures accurately the execution time variation on individual paths due to hardware effects.

This novel and innovative approach combines the advantages of both measurement and static analysis techniques while avoiding their drawbacks. Unlike static analysis, it does not require the expensive and time consuming production of a precise timing model for each new microprocessor variant and its hardware acceleration features, and so is portable to a wide range of different microprocessors. RapiTime is also viable when the only accurate timing model that is available is the microprocessor itself. Further, RapiTime does not require the plethora of manual annotations

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that static analysis alone needs to establish essential information about control flow. This greatly reduces the amount of engineering time required before meaningful results can be obtained, and removes a potential source of errors. Compared to measurement, RapiTime is able to identify the worst-case path and compute the overall WCET of software components from the WCETs of sub-paths when not all of the complete paths through the code have been executed. This significantly reduces the amount of testing required to verify timing correctness.

For the full duration of the NextTTA project, while carrying out the underpinning research, Guillem Bernat was a Lecturer, Antoine Colin and Stefan Petters were Research Associates, and Alan Burns was a Professor in the Computer Science Dept. at the University of York. (Martin Newby, Professor of Statistical Science at City University in London, assisted with some of the probabilistic methods used in [2]; however, the overwhelming majority of the underpinning research was done at the University of York). Antoine Colin left the University of York on 31st Jan 2003, Stefan Petters on 31st July 2004, and Guillem Bernat on 6th October 2005 (on secondment). Prof. Alan Burns remains at the University of York to this day.

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

[1] G. Bernat, A. Colin, S. M. Petters, "WCET Analysis of Probabilistic Hard Real-Time Systems" IEEE Real-Time Systems Symposium (RTSS), December 2002, Austin, Texas, USA.

DOI: 10.1109/REAL.2002.1181582

[2] G Bernat, M. J. Newby, A. Burns, "Probabilistic Timing Analysis: an Approach using Copulas" Journal of Embedded Computing, v1-2, pp 179–194, 2005.

<http://dl.acm.org/citation.cfm?id=1233760.1233763>

[3] A. Colin, S. M. Petters "Experimental Evaluation of Code Properties for WCET Analysis" IEEE Real-Time Systems Symposium (RTSS), Cancun, Mexico, December 2003.

DOI: 10.1109/REAL.2003.1253266

[4] A. Colin, G. Bernat, "Scope Tree: a Program Representation for Symbolic WCET Analysis" In Proc. 14th Euromicro Conference on Real-Time Systems (ECRTS), June 2002, Vienna, Austria.

DOI: 10.1109/EMRTS.2002.1019185

[5] G. Bernat, A. Colin, S. M. Petters, "pWCET a Toolset for automatic Worst-Case Execution Time Analysis of Real-Time Embedded Programs" 3rd Int. Workshop on WCET Analysis, at the Euromicro conference on Real-Time Systems, Porto, Portugal, 1 July 2003. (Available as a technical report <https://www.cs.york.ac.uk/ftpdir/reports/2003/YCS/353/YCS-2003-353.pdf>)

Number of citations: Google Scholar 29th Aug 2013 [1] – 256, [2] – 49, [3] – 52, [4] – 53, [5] – 81. Scopus 29th Aug 2013: [1] – 60, [2] – not indexed, [3] – 11, [4] – 12 (11/11/13), [5] – not indexed. References [1], [3], and [4] best indicate the quality of the underpinning research.

Note that RTSS is widely recognised as the premier conference in the real-time systems field. It is rated A according to the ERA conference rankings 2010. ECRTS is also an A rated international conference.

The research published in [1], [2], [3], [4], and [5] was carried out under the EU funded FP5 project NextTTA (High-Confidence Architecture for Distributed Control Applications) IST 2001-32111 (1st Jan 2002 to 31st Jan 2004, PI Prof. Alan Burns, University of York, funding €150,155.00).

4. Details of the impact (indicative maximum 750 words)
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Impact: The underpinning research was exploited in the development of an innovative Worst-Case Execution time (WCET) analysis technology now called "RapiTime". This technology was transferred to industry via the formation in 2004 of a successful spin-out company; Rapita Systems Ltd. This technology has been deployed on, and is in continuous use on, a number of major long-term aerospace and automotive projects world-wide, examples include:

- [TEXT REMOVED FOR PUBLICATION]: Flight Control Computer (FCC) and the [TEXT REMOVED FOR PUBLICATION] (RapiTime in continuous use since 2006) [11].
- [TEXT REMOVED FOR PUBLICATION]: FADEC (Full Authority Digital Engine Control) for the [TEXT REMOVED FOR PUBLICATION] (Since 2009).
- [TEXT REMOVED FOR PUBLICATION]: (Since 2011).
- Alenia Aermacchi (Italy): Flight Control System for the M-346 military transonic trainer. (Since 2010) [10].
- [TEXT REMOVED FOR PUBLICATION] a European Space Agency [TEXT REMOVED FOR PUBLICATION] (Since 2012).

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- [TEXT REMOVED FOR PUBLICATION]: Used in a proof-of-concept relating to new processes for the development of Flight Control Systems. (Since 2010).
- [TEXT REMOVED FOR PUBLICATION]: Evaluation and tool qualification for use on the [TEXT REMOVED FOR PUBLICATION]. (Since 2008).
- [TEXT REMOVED FOR PUBLICATION]: Development of [TEXT REMOVED FOR PUBLICATION] software modules. (Since 2009).
- [TEXT REMOVED FOR PUBLICATION] control system for small vehicles, [TEXT REMOVED FOR PUBLICATION] (Since 2010).

Other customers since 2008 include [TEXT REMOVED FOR PUBLICATION] and the European Space Agency (ESA).

Note, commercially sensitive detailed quantification of end-user benefits are not available from the above major international companies.

Since 2008, Rapita has also won significant export orders to China worth over [TEXT REMOVED FOR PUBLICATION] via its distributor Cinawind. Customers include: [TEXT REMOVED FOR PUBLICATION].

From 2008/9 to 2012/13, the company's annual revenues have more than doubled [TEXT REMOVED FOR PUBLICATION], with annual profits increasing from [TEXT REMOVED FOR PUBLICATION] to circa [TEXT REMOVED FOR PUBLICATION]. The majority of Rapita's revenues come from products and services based on RapiTime.

Route to Impact: Above we detailed specific exploitation of the technology and impact and during the REF period. Next we detail the evidential link between the underpinning research and that impact. During the EU FP5 NextTTA project members of the RTSRG group, Guillem Bernat, Antoine Colin, Stefan Petters, and Alan Burns, introduced the underpinning research on hybrid measurement-based WCET analysis. This approach combined both measurement and static analysis techniques to accurately estimate the WCET of complex software components running on advanced microprocessors. As part of the project, they also developed a prototype WCET analysis tool called pWCET [5]. This tool was evaluated on an Audi drive-by-wire system. Audi was an industrial partner in the NextTTA project. Audi's expression of interest in pWCET and its capabilities led directly to the formation of a spin-out company to transfer this technology into industry.

In 2004, members of the RTSRG; Guillem Bernat, Ian Broster, Antoine Colin, and Robert Davis, and the University of York founded a spin-out company called Rapita Systems Ltd. (www.rapitasystems.com) to commercialise the technology and bring it to market. All rights to the technology and prototype tools were transferred to the company by the University of York which became a shareholder in the company.

In 2005, Rapita Systems received £200k of funding from Viking Investments Ltd. and an associated group of Business Angels [6]. Following the initial technology transfer, the pWCET prototype was re-implemented as a commercial quality tool and re-branded as RapiTime. RapiTime has since been extended to support analysis of systems written in C++ as well as the C, and Ada programming languages, and has recently been complemented by a Code Coverage tool (RapiCover) which uses the underpinning RapiTime technology for code instrumentation and analysis. Together, RapiTime and RapiCover are part of the Rapita Verification Suite (RVS).

In 2006, BAE Systems used RapiTime on the Hawk Advanced Jet Trainer project [7]. Here, RapiTime was used to identify opportunities for WCET reduction, thus creating headroom for new functionality to be added to the system, while avoiding the need for a costly hardware upgrade. Using RapiTime, BAE identified that just 1% of hundreds of thousands of lines of code contributed 29% of the overall WCET. Further, by focusing optimisation efforts on this 1% of the code, they were able to reduce the WCET by 23% [8]. Further, RapiTime was quantified as being able to identify timing problems with less than 10% of the effort of previous approaches, potentially saving months of work. As a result Rapita received a BAE chairman's award for Innovation in the category Transferring Best Practice.

Since 2008, Rapita has focused on sales of its RVS product, centred on RapiTime, to customers in the aerospace and automotive markets. This impact has been described in the previous section.

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The RTSRG at the University of York continues to have strong links with Rapita; Prof. Alan Burns is chairman of the Board, while Dr. Robert Davis is a Non-Executive Director of the company and also a member of the RTSRG.

Beneficiaries: RapiTime enables companies in the aerospace and automotive electronics industries to reduce the time and cost required to obtain confidence in the timing correctness of the systems they develop. It provides a cost-effective means of targeting software optimisation, such that new functionality can be added to existing systems without the need for expensive hardware upgrades. Further, RapiTime is portable across a wide range of different microprocessors, meaning that companies can use the same technology across multiple projects without the need for re-training or adoption of multiple solutions.

[TEXT REMOVED FOR PUBLICATION], the major [TEXT REMOVED FOR PUBLICATION] aerospace supplier, described the benefits of using RapiTime to identify timing problems during continued development of the Flight Control System for the [TEXT REMOVED FOR PUBLICATION] as follows: *“The biggest benefit that RapiTime brought to our development process was just how quickly we could get comprehensive timing measurements from our tests. Not only did we reduce our effort requirements for the testing, but we could use our results in ways that were infeasible before. It is now significantly faster for us to identify a timing issue, update the software to resolve the issue, test the updated software and verify that it’s fixed”* - Wayne King, Engineering Fellow, [TEXT REMOVED FOR PUBLICATION] – 30th July 2009 [9].

Without RapiTime, the timing measurement and analysis process needed to determine WCETs has to be done manually. This is a painstaking and error prone process that takes considerable time and effort. It also needs to be repeated when changes are made to the application software. Further, the manual process provides no information about the worst-case path, or the contribution of different sections of code to the WCET. This makes code optimisation an ad-hoc, ineffective and inefficient process, as optimising for the worst-case is very different from optimising for the average case.

Alenia Aermacchi engineers working on the M-346 Flight Control System said, *“the main advantage [of using RapiTime] is the possibility to identify software bottlenecks that can be subject to optimisation. Without RapiTime the mandatory code optimisation would have been done without the knowledge of where to concentrate the efforts.”* [10].

Overall, *“Using RVS, customers have cut the worst-case execution time of large scale, legacy applications by up to 50% with only a few days effort, and significantly reduced unnecessary testing and instrumentation overheads”* [11].

Rapita has offices in York and opened a second office in Cambridge in May 2012. Rapita has created and sustained [TEXT REMOVED FOR PUBLICATION] high technology jobs [9]. The success and indeed the existence of the company is a consequence of the underpinning research as described in the narrative.

Corroboration of all of the facts presented above about Rapita and its customers etc. can be obtained from [9].

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

[6] <http://www.rapitasystems.com/system/files/yabawinter05news.2.pdf>

[7] http://www.rapitasystems.com/system/files/CaseStudy_BaE_Hawk_2.pdf

[8] G. Bernat, R.I. Davis, N. Merriam, J. Tuffen, A. Gardner, M. Bennett, D. Armstrong. “Identifying Opportunities for Worst-case Execution Time Reduction in an Avionics System”. *Ada User Journal* pp. 189-194, Volume 28, Number 3, Sept 2007.

[9] Chief Financial Officer (CFO), Rapita Systems Ltd.

[10] http://www.rapitasystems.com/system/files/Aermacchi_case_study_0.pdf

[11] http://www.rapitasystems.com/system/files/CaseStudy_FlightControlSystem_1.pdf