Institution: University of York		
Unit of Assessment: 11 - Computer Science and Informatics		
Title of case study: RapiTime		
Period when the underpinning research was undertaken: 2002-2005		
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:**
Alan Burns	Professor	Jan 1990 - present
Guillem Bernat	Lecturer	Jan 2001 - Sept 2008
Stefan Petters	Research Associate	Apr 2002 - July 2004
Antoine Colin	Research Associate	Nov 2002 - Jan 2003
Period when the claimed impact occurred: 2014-2019		
Is this case study continued from a case study submitted in 2014? Yes		

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

Research from the Real-Time Systems Research Group at the University of York 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 Germany, Spain, Italy, India, France, UK, USA, China, Brazil, Greece, Netherlands, Portugal, Canada, Sweden, and Japan. Key customers include leading companies such as: [text removed for publication]. Since 2014, Rapita has won significant export orders to [text removed for publication] with reference sales made throughout the organisation. Further, [text removed for publication] is using RapiTime to analyse timing analysis of next generation [text removed for publication] processors used in all of its new [text removed for publication]. In the 2018-19 financial year, Rapita's annual revenues exceeded [text removed for publication]. As of March 2019, Rapita employed over [text removed for publication] people at its offices in York, and [text removed for publication] people in the USA through Rapita Systems Inc.

2. Underpinning research (indicative maximum 500 words)

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.

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 techniques for WCET analysis **[3.1]**, **[3.2]**, **[3.3]**, **[3.4]**, and **[3.5]**, 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 determines 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 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.

While carrying out the underpinning research, Alan Burns was a Professor, Guillem Bernat was a Lecturer, and Stefan Petters and Antoine Colin were Research Associates 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 **[3.2]**; however, the overwhelming majority of the underpinning research was done at the University of York. Prof. Alan Burns started work at the University of York in Jan 1990 and remains there to this day Guillem Bernat was employed by the University of York from Jan 2001 to Sept 2008. He was seconded to Rapita Systems from Oct 2006 to Sept 2008. Stefan Petters was employed by the University of York from Apr 2002 to July 2004. Antoine Colin worked at the University of York as a visiting post-doc researcher, paid on a French MoD grant, from Oct 2001 to Oct 2002; he was then employed by the University of York as a Research Associate from Nov 2002 to Jan 2003. His main contributions to the underpinning research were made prior to Jan 2003.

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

[3.1] 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. https://doi.org/10.1109/REAL.2002.1181582 [peer reviewed CONFERENCE]
[3.2] 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 [peer reviewed JOURNAL]
[3.3] A. Colin, S. M. Petters "Experimental Evaluation of Code Properties for WCET Analysis" IEEE Real-Time Systems Symposium (RTSS), Cancun, Mexico, December 2003. https://doi.org/10.1109/REAL.2003.1253266 [peer reviewed CONFERENCE]

[3.4] A. Colin, G. Bernat, "Scope Tree: a Program Representation for Symbolic WCET Analysis" Euromicro Conference on Real-Time Systems (ECRTS), June 2002, Vienna, Austria. https://doi.org/10.1109/EMRTS.2002.1019185 [peer reviewed CONFERENCE]
[3.5] 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 (ECRTS), Porto, Portugal, 1 July 2003. (Available as a technical report from the White Rose repository:

http://eprints.whiterose.ac.uk/158720/1/YCS_2003_353.pdf published in Jan 2003) [peer reviewed WORKSHOP]

References **[3.1]**, **[3.3]**, and **[3.4]** best indicate the quality of the underpinning research. RTSS **[3.1]**, **[3.3]** is widely recognised as the premier conference in the real-time systems field. It is ranked A* according to the CORE conference rankings (http://portal.core.edu.au/conf-ranks/). Similarly, ECRTS **[3.4]** is an A ranked international conference according to CORE. Papers in both conferences are peer-reviewed by at least 3 reviewers.
The research published in **[3.1]**, **[3.2]**, **[3.3]**, **[3.4]**, and **[3.5]** 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 GBP93,847).

4. Details of the impact (indicative maximum 750 words)
In the first part of this section, we provide necessary details of the Route to Impact, describing how the underpinning research was exploited in the development of an innovative Worst-Case Execution time (WCET) analysis technology now called "RapiTime", and transferred to industry via the formation of a successful spin-out company, Rapita Systems Ltd. (https://www.rapitasystems.com/), hence providing the evidential link between the underpinning research and the impact in the relevant REF period (i.e. since Aug 2013). The Impact during the REF period is then detailed in the second part of this section.

Route to impact:
During the EU FP5 NextTTA project (1st Jan 2002 to 31st Jan 2004) 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 **[3.5]**. 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 GBP200,000 of funding from Viking Investments Ltd. and an associated group of Business Angels. Following the initial technology transfer, the pWCET prototype was re-implemented as a commercial quality tool and re-branded as "RapiTime". RapiTime was then extended to support analysis of systems written in C++ as well as the C, and Ada programming languages.

The low-overhead tracing, source code instrumentation, and parsing technology developed as part of RapiTime were used as the basis for two complementary products: (i) a code coverage tool (RapiCover) and (ii) an on-target test solution (RapiTest) that automates the creation and execution of unit, integration and system tests. Together, RapiTime, RapiCover, and RapiTest form part of the Rapita Verification Suite (RVS).
From 2008 to 2014, Rapita's revenues increased from [text removed for publication], and as of Aug 2013, Rapita employed [text removed for publication] people in its offices in York and Cambridge.

Impact during the REF period:
Since 2014, Rapita has focused on sales of its RVS product, including RapiTime, RapiCover, and RapiTest, to customers (https://www.rapitasystems.com/about/customers) in the aerospace and automotive markets.

RapiTime (https://www.rapitasystems.com/products/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.

RapiCover (https://www.rapitasystems.com/products/rapicover) reduces the time and effort required for companies to obtain structural code coverage data for their critical embedded software. RapiCover achieves this by integrating with existing software build systems, and utilising extremely low overhead, on-target tracing technology. This reduces the number of builds needed to collect coverage data, eliminating unnecessary testing time and effort.

RapiTest (https://www.rapitasystems.com/products/rapitest) drives the inefficiencies out of functional testing in critical software verification projects, by automating the creation and execution of unit, integration and system tests. It reduces the cost of software verification, particularly in the avionics industry.

RapiTime technology has been deployed on, and in continuous use (within the REF period) on a number of major long-term aerospace projects world-wide, examples include:

- [text removed for publication]: Flight Control Computer (FCC) and the Cockpit Displays for the [text removed for publication] (RapiTime in continuous use since Aug 2013, started in 2006).
- [text removed for publication]: FADEC (Full Authority Digital Engine Control) for the [text removed for publication] (RapiTime in continuous use since Aug 2013, started in 2009).
- [text removed for publication]: ARBS (Aerial Refueling Boom System) for the [text removed for publication] (RapiTime in continuous use since Aug 2013, started in 2011).
- [text removed for publication]: Flight Control System for the [text removed for publication] (RapiTime in continuous use since Aug 2013, started in 2010).
- [text removed for publication] a European Space Agency experimental [text removed for publication] (RapiTime in continuous use since Aug 2013, started in 2012).
- [text removed for publication]: Used in a proof-of-concept relating to new processes for the development of Flight Control Systems. (RapiTime in continuous use since Aug 2013, started in 2010).
- [text removed for publication]: Evaluation and tool qualification for use on the [text removed for publication]. (RapiTime in continuous use since Aug 2013, started in 2008).
- [text removed for publication]: Development of AUTOSAR software modules. (RapiTime in continuous use since Aug 2013, started in 2009).
- [text removed for publication]: Flight management system (since 2015), [text removed for publication] Systems (since 2015), [text removed for publication] (since 2015), [text removed for publication] (since 2014), more than 10 projects, certifications and new developments during 2014-2020.
- [text removed for publication]: all new [text removed for publication], using the [text removed for publication] processor, analysed by RapiTime. (Since 2014).
- [text removed for publication]: started use in 2015, developed onto new multicore platform since 2019.
- [text removed for publication]: started use in 2017, broader adoption in 2019, new multicore RapiTime use since 2019.
- [text removed for publication], started RapiTime use in 2019 for new project.
- [text removed for publication], started RapiTime use in 2018.
- [text removed for publication], RapiTime and multicore analysis since 2019.

- Multiple companies in [text removed for publication] adoption from 2016 to 2020, various projects. [text removed for publication].
- Projects have also started with [text removed for publication] in 2017, [text removed for publication] in 2019, and [text removed for publication] in 2019. [text removed for publication].

The majority of Rapita's revenues come from the Rapita Verification Suite (RVS) products and services based on the RapiTime technology.

As an exemplar, [text removed for publication] has been a major user of the Rapita RVS products, based on the RapiTime technology since 2014. Today, they are a key customer for Rapita, using several RVS tools including both RapiCover and RapiTest.

The [text removed for publication] work started in 2013, to see if the low overheads of RapiTime could be used to monitor an unusual and esoteric system. The trial was successful, and the company adopted a few licences for the verification of an update to a key [text removed for publication] project. As the technology proved itself and confidence in the tools increased, additional [text removed for publication] development projects, primarily cockpit and controls systems, started to use RVS. From 2017 onwards, these projects have been through multiple certifications with the FAA and other bodies, using the certification kits also provided by Rapita. Today, the [text removed for publication] units tested by RVS are flying in at least four commercial [text removed for publication] aircraft.

Without RVS, the timing measurement, code coverage analysis and testing of the safety critical software would be done either manually or with other less powerful tools. The low-overhead of the original RapiTime technology has been successfully applied to enable efficient measurement of structural code coverage of systems at [text removed for publication]. The benefit is that more of the software can be tested at once, so that the time and cost of testing is lower. In a key avionics control systems upgrade, before RVS 15 test runs were required, which was reduced to only 2 using RVS, meaning that the testing costs 13% of the original. Rapita received the following feedback from a senior engineer at [text removed for publication] in 2019: "This is an excellent tool and everyone on the project likes what it can do".

In 2016, Rapita was acquired by Danlaw Inc to support its growth and expansion into the automotive and aerospace industries. In the 2018-19 financial year, Rapita's annual revenues exceeded [text removed for publication] (up from [text removed for publication] for the financial year prior to the start of the REF period). Further the number of employees has increased from a total of [text removed for publication] as of August 2013, to over [text removed for publication] in York, and [text removed for publication] in the USA (Rapita Systems Inc.) as of April 2020. The success and indeed the existence of the company is a consequence of the underpinning research as described in the narrative.The Department of Computer Science at the University of York continues to have strong links with Rapita, through joint work on UK Research and Innovation projects such as SECT-AIR and HICLASS.

All of the facts presented above about the customers, projects, revenues, and headcount of Rapita Systems Ltd., are confirmed and corroborated in **[5.1]**.

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

[5.1] Letter of corroboration from General Manager, Rapita Systems Ltd. Atlas House, Osbaldwick Link Road, York YO10 3JB, United Kingdom.