# Problem **solver**

**Dr Tim Willemse** and **Professor Dr Jan Friso Groote** discuss their involvement in an international team of researchers who have developed specific software to detect inherent problems in the control system of the Compact Muon Solenoid experiment at CERN

**To provide some background, can you briefly describe the Compact Muon Solenoid (CMS) experiment at CERN's Large Hadron Collider (LHC)? How is software controlling the experiment structured?**

**TW:** The CMS experiment at CERN is one of four large physics experiments designed to study the wide range of particles produced from the high energy collisions in the LHC. The software controlling this experiment has a very hierarchical structure and consists of 25,000-30,000 components, each behaving as finite state machines (FSMs). These are arranged in a tree structure and only communicate with FSMs that are immediately above or below them. Control commands are propagated and refined up the tree of FSMs. State changes of FSMs are sent down the tree. This architecture allows the immense control problem to be decomposed into smaller, more manageable problems.

**Are there concerns with CMS's hierarchical control software for which you have devoted your research efforts in this project?**

**TW:** CERN's engineers observed that subsystems of the control system became non-responsive from time to time. Our contact at CERN had a hunch that it might be related to the software. But the complexity of this software system meant that there was no easy way to prove this. When asked if we could help identify the root cause, we started by modelling parts of the control system and applying our tools to analyse these parts. This allowed us to unearth several issues that caused the control system to become non-responsive. Based on these findings, we have developed dedicated tools that are now incorporated in the development process of CMS's FSMs.

**What is your specialism and who comprises your team?**

**TW:** We specialise in analysing complex software systems. Our background enabled us to quickly zoom in on the core of the problem in the control system. For instance, we had reason to believe that the non-responsiveness of the control software was caused by subtle software bugs that cause a subsystem to enter into an endless computation, flooding the network. These bugs – called livelocks – are virtually impossible to find using testing. Our technology allows such bugs to be detected and resolved. Indeed, for the control system of the CMS experiment, we detected a large number of different livelocks.

Our project team consists of computer scientists from Eindhoven University of Technology and Twente University in The Netherlands, Dr Frank Glege, a physicist at CERN, and Professor Dr Rance Cleaveland from the University of Maryland, USA. Most of the theoretical research is carried out by two PhD students: Maciej Gazda, working at Eindhoven University of Technology, supervised by Groote and me; and Gijs Kant, working at Twente University, supervised by Professor Jaco van de Pol. We have also worked with excellent Master's students from our university and from CERN, and also one of our PhD students, Jeroen Keiren.

**Do you foresee similar problems cropping up in the other experiments at the LHC, and also in experiments at other facilities?**

**TW:** As it turns out, the other large experiments running at the LHC use the same architecture for controlling their experiments. The technology that we have developed for CMS is now also used for the other experiments.

**JF:** The phenomena that we've observed in CMS's control system are really universal to all companies that produce systems involving large-scale software solutions. For example, we observed similar phenomena in the Atacama Large Millimeter/submillimeter Array (ALMA) project run by the European Southern Observatory.

**How will research progress over the coming months and years? Will you be changing your research focus?**

**TW:** At the beginning of the project, we mainly focused on solving problems our collaborators at CERN found important. Using our existing theory and tools, we were indeed able to pinpoint the causes of those problems, and solve them. But some of the problems that were deemed to be less important at that time actually posed more of a challenge to us. We are now working on improving our theory to be able to effectively solve those problems as well. We are anxious to apply our technology to other systems within CERN and elsewhere.

# Under **control**?

The increasing complexity of control systems used in experiments at the **Large Hadron Collider** has made it necessary to develop toolkits to model and analyse them in order to detect and fix the problems that arise

**THE COMPACT MUON SOLENOID (CMS)** experiment at the Large Hadron Collider (LHC) near Geneva is a particle detector with a diameter of 15 metres and a weight of approximately 15 tonnes. It consists of seven subdetectors which are capable of stopping, tracking and measuring the particles produced by high energy proton collisions. The LHC accelerates protons to a velocity close to that of light in order to create head-on collisions, and the energy released from this process is transformed into mass in the form of short-lived particles. CMS serves to observe and study the particles and phenomena resulting from these high energy reactions. Whilst it makes more accurate measurement of the properties of known particles, it is also on the lookout for novel phenomena.

## CONTROL SYSTEM

The experiment is monitored in real time by over 27,500 finite states machines (FSMs) organised in a hierarchical manner to form the control system. These FSMs are relatively simple, with each one having an average of five logical states, each state being in one of two possible phases. However, complexity arises out of the interaction between the components of the control system. At the top of the hierarchy lies a single controlling FSM, whilst the bottom typically consists of myriad devices (both hardware and software). Commands are sent downwards whilst status and alarms travel in the opposite direction. The average depth of the architecture is nine nodes, with a maximum depth of 11 and a minimum depth of three. The principal role of this hierarchical control system is to switch the detector on and off.

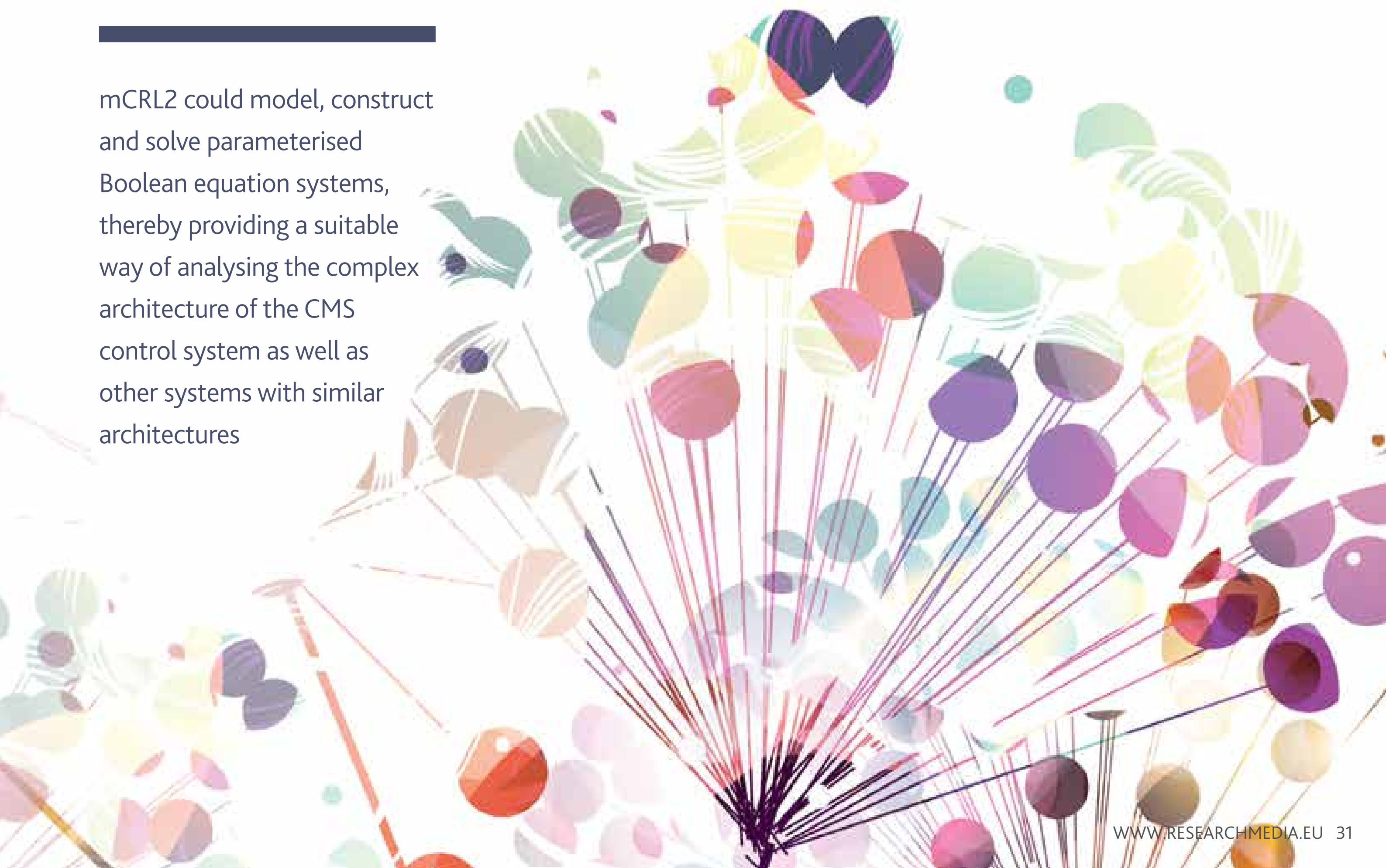
Unfortunately, this complexity inherent to the system is such that recently the entire system became unpredictable. The software lost track of parts of the experiments and, whilst the CMS researchers could analyse clusters of FSMs, the problems faced by the team required complete system verification. Because the CMS research group comes largely from a physics background, the researchers called on the expertise of Dr Tim Willemse from Eindhoven University of Technology, who leads an international team of scientists. "For systems of this size and complexity, a thorough understanding of the problems can only be obtained by modelling the essential parts of the system and analysing these models," he explains.

## FINDING A LANGUAGE

In order to analyse and model the control system, it is first necessary to translate the hierarchy of FSMs (described in State Manager Language) into a language suited to the problem at hand. There exist many logics of different orders with varying expressive powers and more or less complex syntaxes. To carry out the task, the team needed to find a sufficiently expressive logic which was not unnecessarily complicated. "Propositional logic reasons about propositions that can be either true or false, and their conjunction, disjunction and logical negation, but it has no variables over which one can quantify," Willemse expands. "In a nutshell, first-order logic essentially extends propositional logic by adding variables over which one can quantify."

The logic chosen by the team is an extension of this first-order logic called parameterised

mCRL2 could model, construct and solve parameterised Boolean equation systems, thereby providing a suitable way of analysing the complex architecture of the CMS control system as well as other systems with similar architectures



## INTELLIGENCE

### VERIFICATION OF COMPLEX HIERARCHICAL SYSTEMS

### OBJECTIVES

To resolve problems in the hierarchical control systems used in the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC), and then apply these solutions to other experiments at the LHC and beyond.

### TEAM MEMBERS

**Professor Dr Rance Cleaveland**, University of Maryland, USA

**Dr Frank Glege**, CMS CERN, Switzerland

**Professor Dr Jan Friso Groote**; **Dr Tim Willemse**; **Maciej Gazda**; **Jeroen Keiren**, Eindhoven University of Technology, The Netherlands

**Professor Dr Jaco van de Pol**; **Gijs Kant**, Twente University, The Netherlands

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**TIM WILLEMSE** earned a PhD in Computer Science in 2003 from Eindhoven University of Technology, where he returned In 2006 as an assistant professor. Prior to that, he worked part-time at ASML and Radboud University, where he developed and applied model-based testing technology. His research interests include algorithms and logics for verification and application to ensure the correctness of complex software.

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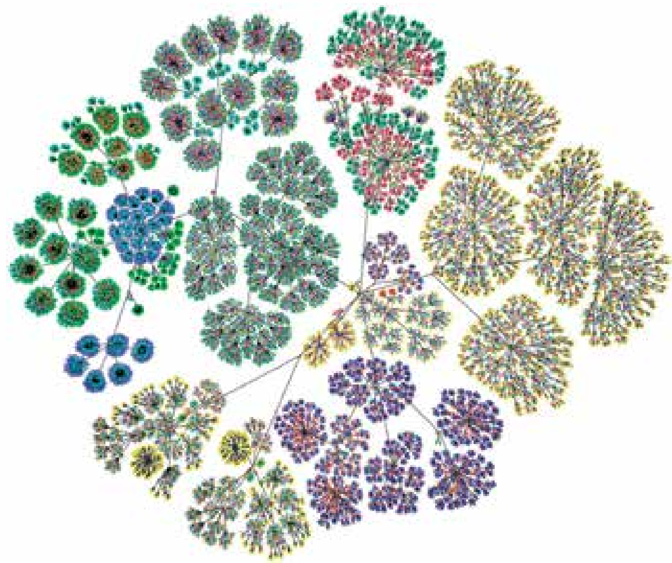

An illustration of the communication hierarchy in the control software. Each small software component is one of the coloured dots in the figure, and the lines between two dots indicate that the components they represent are connected and communicate directly with one another. Same-coloured nodes in the figure indicate that the components run the same software programs, whereas different coloured nodes run different programs.

Boolean equation systems (PBES) which is essentially a first-order logic with fixpoints. These fixpoints allow limited quantification over predicates whilst avoiding the pitfalls of second-order logic (which quantifies over all predicates). Willemse's work relies on translating the analysis of the CMS control system to a PBES solving problem.

A strength of PBES is that it includes techniques from multiple fields in computer science which are not typically associated. This means that the researchers can use several different methods to find PBES solutions, with algorithms similar to game theory and Gaussian elimination techniques, for instance. Solving PBES using a multitude of algorithms from different areas increases confidence in the solutions, making them more certain than relying on a single method to solve the problem.

### CREATING A TOOLSET: MCRL2

Having found a suitable formalism, Professor Dr Jan Friso Groote, Willemse and their collaborators developed a toolset named mCRL2 which could model, construct and solve PBES, thereby providing a suitable way of analysing the complex architecture of the CMS control system as well as other systems with similar architectures. The mCRL2 language involves three parts: a data language, a process language and a modal language.

The main purpose of the mCRL2 toolset is to provide correct software by modelling it and to subsequently visualise the behaviour using two- and three-dimensional technology. This process led to the discovery and elimination of serious problems in most programs, protocols and distributed algorithms tested by the team, which would otherwise have remained present.

The outcome of the research was a success, as the CMS group has decided to translate the FSM-based control system into mCRL2. Other experiments at the LHC using control systems with similar architectures have also adopted the techniques developed by Willemse's team. Although mCRL2 is designed with a specific purpose in mind, is an 'academic' toolset and has a steep learning curve, it has also found applications in other areas of academia and is increasingly being used commercially.

### FROM PARTICLE PHYSICS TO THE MARKETPLACE

As mentioned, technologies developed for research in fundamental physics, although seemingly removed from other areas of society, can find their way into applications outside the field. However, the lack of a standardised language and complexity of such toolsets has left a disparity between the complex software and the workforce of programmers used to more straightforward toolsets. Groote explains: "It requires a certain degree of mathematical maturity to understand which way of modelling is most effective. Although there are general guidelines for modelling systems effectively, the use of specific guidelines must be reconsidered on a case by case basis".

In order to bridge this gap and encourage the utilisation of the software, the researchers have made it free to use and contribute to. They also provide introductory information about the methods they use. This strategy of making the software accessible has seen an increase in the users of the mCRL2 toolset in the academic world.

The phenomena found in the CMS control system are shared by other software including complex systems produced by private companies. In addition, companies in The Netherlands such as Verum and Imtech which develop complex embedded software use academic toolsets such as mCRL2 for verification purposes. This has opened the door for multinationals like Philips to propose using formal methods in the development of their products.