(Auto)Focus approaches and their applications: A systematic review

Maria Spichkova
School of Science, RMIT University, 414-418 Swanston Street, 3001, Melbourne, Australia
maria.spichkova@rmit.edu.au

Keywords:
Software Engineering, Formal Methods, Specification, Verification, Tool-support

Abstract:
Focus, a framework for formal specification and development of interactive systems, was introduced approx. 25 years ago. Since then, this approach was broadly used in academic and industrial studies, as well as provided a basis for a number of other frameworks focusing on particular domains, and for the AF3 modelling tool. In this paper, we provide a literature review of the corresponding approaches, academic case studies and industrial applications of these methods.

1 INTRODUCTION

Focus, a framework for formal specification and development of distributed interactive systems, provides models and formalisms for a stepwise specification and development. Focus was introduced by Broy et al. [19] approx. 25 years ago. Since then, the framework was extended and gave a basis for a number of other approaches. Many case studies from several application domains were conducted, within both academic and industrial projects. One of the most comprehensive description of the formal background of the framework was presented by Broy and Stølen [26], and became a highly cited publication (more than 540 citations). The goal of this approach is to support a modular system development with the help of component specifications, having precisely identified interfaces and formal refinement concepts. Focus is based on a clear mathematical theory and aims on system development carried out in a systematic way.

The tool-support for this approach is provided by the AutoFocus CASE tool. The prototype was initially presented by Broy et al. [22], and later extended and refined by two next generations of the tool. The third generation of AutoFocus, AutoFocus3 or AF3, is a powerful opensource tool. It’s emphasis is on the development of embedded systems using models from the requirements to the hardware architecture. The latest version of AF3 provides advanced features to support the user: formal analyses, synthesis methods, space exploration visualization, etc.

The research on the Focus-related approaches is an active topic. The most recent related works were presented by Alzahrani et al. [2], where aims was to apply property-based testing on formal models with temporal properties, and by Kanav and Aravantinos [36], introducing the modular transformation from AF3 to the nuXmv symbolic model checker. As over the last 25 years many theoretical and applies work was conducted within the Focus approach, an overview of existing work is required. In this paper, we are going to provide a systematic review of the corresponding approaches as well as on the case studies they were applied on.

Outline: Section 2 provided a high-level overview of the Focus ideas. Spatio-Temporal view on modelling of interactive systems is presented in Section 3. Section 4 discusses the tool support for the approach. Section 5 introduces methodological extensions of the Focus approach as well as the frameworks built on its basis. Section 6 reviews the academic and industrial case studies conducted using Focus or related approaches. Section 7 discusses human-oriented aspects of the related formal methods. Finally, Section 8 summarises the paper.
2 FOCUS

A distributed system in FOCUS is specified by its logical components connected via channels, which are directed and order preserving. Components work independently of each other or interact, exchanging information in terms of messages of specified types.

The formal meaning of a FOCUS specification is an input/output relation, i.e. the relation between the communication histories for the external input and output channels. The specifications can be

- structured into a number of formulas each characterizing a different kind of property;
- elementary or composite:
  - Elementary specifications can be untimed, timed, and time-synchronous;
  - Composite specifications are built hierarchically from the elementary ones.

The central concept in FOCUS are streams, that represent communication histories of directed channels. Streams in FOCUS are functions mapping the indexes in their domains to their messages. For any set of messages \( M \), \( M^\omega \) denotes the set of all streams, \( M^\omega \) and \( M^* \) denote the sets of all infinite and all finite streams respectively. \( M^\omega \) denotes the set of all timed streams, \( M^\omega \) and \( M^\omega \) denote the sets of all infinite and all finite timed streams respectively.

\[
\begin{align*}
M^\omega & \overset{\text{def}}{=} M^* \cup M^\omega \\
M^* & \overset{\text{def}}{=} \bigcup_{n \in \mathbb{N}} ([1..n] \rightarrow M) \\
M^\omega & \overset{\text{def}}{=} \mathbb{N}_+ \rightarrow M
\end{align*}
\]

Thus, timed stream is represented by a sequence of messages and time ticks, the messages are also listed in their order of transmission. The ticks model a discrete notion of time.

\[
\begin{align*}
M^\omega & = M^\omega \cup M^\omega \\
M^* & = \bigcup_{n \in \mathbb{N}} ([1..n] \rightarrow M \cup \{\sqrt{\}\}) \\
M^\omega & = \mathbb{N}_+ \rightarrow M \cup \{\sqrt{\}\}
\end{align*}
\]

3 SPATIO-TEMPORAL VIEW: FOCUS\(^{ST}\)

Timing aspects of FOCUS as well as the corresponding optimisations of the specification layout were discussed in \[57\], which was the first step towards elaboration the FOCUS\(^{ST}\) framework.

In both frameworks, specifications are based on the notion of streams. However, in the original FOCUS input and output streams of a component are mappings of natural numbers \( N \) to single messages, whereas a FOCUS\(^{ST}\) stream is a mapping from \( N \) to lists of messages within the corresponding time intervals. Moreover, the syntax of FOCUS\(^{ST}\) is particularly devoted to specify spatial (S) and timing (T) aspects in a comprehensible fashion, which is the reason to extend the name of the language by \( S^T \).

The FOCUS\(^{ST}\) specification layout \[63, 64\] is similar to FOCUS (which layout was inspired by Z specification language, cf. \[83, 84\]), but it has many new features to increase the readability and understandability of the specification. The FOCUS\(^{ST}\) specification layout is based on human factor analysis within formal methods (see Section 7).

In FOCUS\(^{ST}\) specifications, input and output streams of a component are always timed, as spatio-temporal aspects are the core of the framework. The (timed) streams are mappings from \( N \) to lists of messages within the corresponding time intervals. Thus, these streams are infinite per default, but they could be empty completely or from a certain point which is represented by empty time intervals \( \langle \rangle \). More precisely, FOCUS\(^{ST}\) has streams of two kinds:

- **Infinite timed streams** (denoted by \( M^\omega \)) are used to represent the input and the output streams;
- **finite timed streams** (denoted by \( M^\omega \)) are used to argue about a timed stream that was truncated at some point of time.

Infinite timed streams of type \( T \) are defined by a functional type

\[ \mathbb{N} \rightarrow T^* \]

Finite timed streams of type \( T \) are defined by list of lists over this type, i.e.,

\[ (T^*)^* \]

where \( T^* \) denotes a list of elements of type \( T \).

The FOCUS\(^{ST}\) ideas were applied within the approach on an intelligent route planning for a public transport system within a sustainable Smart City, cf. \[63, 77\].

Spatio-temporal models for formal analysis and property-based testing were presented in \[11, 22\] by Alzahrani et al. The authors aimed to apply property-based testing on FOCUS\(^{ST}\) and TLA models with temporal properties.
4 AUTOFOCUS

AutoFocus tool was developed based on the Focus theory. The first two prototype versions were replaced by AF3 (AutoFocus 3, cf. [33]) tool that provides a various functionalities and supports several development phases. AF3 embeds the core modelling artefacts, is open source, and has a well defined formal syntax behind all its modelling elements. Source code of AutoFocus3 models are coded in XML, which makes it easy to parse and to analyse. The tool was applied as a part of tool chain within a number of development methodologies, cf. Section 5.

Höltl et al. proposed an idea of AutoFocus tool chain and its application for the development of safety-critical systems [34, 35]. An extended and refined version of the approach was later presented in [66]. This approach also was elaborated using AutoFocus 2 and allows a direct application within AF3.

Campetelli et al. [27] introduced an approach to a user-friendly model checking integration in model-based development using AF3. The approach supports support two different model checkers for the model and implementation code verification: SMV and TVARC.

Kondeva et al. [37] presented how the integrated system views on several levels of abstraction are implemented in AF3, to allow the development of embedded systems.

Teufl et al. [86] presented an integrated with AF3 tooling-framework to experiment with model-based Requirements engineering.

Cimatti and Tonetta [29] introduced a temporal logics approach to contract-based design, integrated within AF3.

AF3 tooling concepts for model-based development of embedded systems was presented in [8].

A number of approaches on scheduling and deployment were also integrated within AF3. Voss and Schätz presented an approach on scheduling shared memory multicore architectures in AF3 using SMT solvers [89], as well as an approach on deployment and scheduling Synthesis for mixed-critical shared-memory applications [90].

An approach on generating formal specifications from system AF3 models was presented in [82]. Applying this approach would allow to solve the problem with outdated system documentation by making the documentation updates automatically: an up-to-date formal specification could be generated from the model if the model is frequently changed. The next step in this detection was presented in [87]; this approach allowed generation of natural language specifications from AF3 models.

5 METHODOLOGIES

A number of software and system development methodologies were introduced involving Focus or the framework created in its basis, as well as involving an extensive use of AutoFocus tools.

One of the core features of the current Focus framework, the specification of the black box behaviour of data flow components by characterizing the relation between the input and the output histories, was initially introduced in [25]. The authors distinguished between three main specification classes: time-independent specifications, weakly time-dependent and strongly time-dependent specifications. Data flow components were formally specified by sets of timed stream processing functions. Specifications describe such sets by logical formulas. The proposed solution allowed to handle the Brock/Ackermann anomaly [5]. A further analysis of considering a component as a black box that is a physical encapsulation of related services was presented in [12]. Philipps and Rumpe proposed a stepwise refinement of data flow architectures, cf. [42].

Another core feature of the current Focus framework, a method for the specification of reactive asynchronous components with a concurrent access interface, was discussed in [9].

The approach for structured specifications and implementation of non-deterministic data types was introduced in [43].

Stolen used relations on Focus streams to solve the RPC-memory specification problem, cf. [85].

Broy applied the Focus-based theory to introduce a logical basis for component-based system engineering [13] as well as for specification of interface behaviour of multifunctional systems [19], i.e., systems that offer a variety of functions for different purposes and use cases. In [15], service hierarchies specify multifunctional systems in terms of services (provided sub-functions) taking into account their mutual relationships and dependencies. Each service is specified independently and the specification is added to the service hierarchy, which then describes the functionality of multifunctional systems.

The Janus approach [15, 23] was introduced to
formally design of services and layered architectures, based on the FOCUS theory of distributed systems. A Janus service, like a FOCUS component, has a syntactic interface, but, in comparison to a component, a service has a partial behaviour.

A methodology for modularised specification and verification of distributed time-triggered systems was proposed in [7]. The authors applied FOCUS to specify the systems formally.

A number of FOCUS-related works were focusing on refinement aspects: from a general analysis of compositional refinement of interactive systems [11] as well as the notions of abstraction and causality on the specification level [14] to the refinement-based verification of interactive systems [48] and its relation to the architectural aspects of software and system development [63]. The corresponding methodology of architectural decomposition was discussed in [53]. Transformation of semi-formal requirements to formal FOCUS specifications was proposed in [61].

A specification and proof methodology “FOCUS on Isabelle” [82] supports an alignment on the future proofs during specification phase to make the proofs simpler and appropriate for application not only in theory but also in practice. Given a system represented in FOCUS or FOCUS$^{ST}$, the methodology allows us to verify system properties by translating the specification to a Higher-Order Logic and subsequently using an interactive semi-automatic theorem prover [41], or the point of disagreement will be found. Another advantage of the methodology is a well-developed theory of composition, both for general and cryptographic properties [67] [55].

Feilkas et al. presented a methodology for the top-down development of automotive software systems [31] [32]. The core artefact applied within the methodology was AutoFocus tool and the corresponding extension for test case generation. The methodology was elaborated using AutoFocus 2, however, it can be applied without any changes for AF3. An extension of this FOCUS-based methodology to the domain of cyber-physical systems was proposed in [65].

Vogelsang et al. [38] proposed a model-based approach that starts from informal use cases and enables a stepwise formalization of functional requirements to be linked to the architecture of the system. The approach utilised AF3 as the modelling framework.

An approach introduced by Doby et al. [30] utilized FOCUS to provide an efficient hazard and impact analysis for automotive mechatronics systems.

Another approach based on FOCUS$^{ST}$ allows analysis of component dependencies [61]. This was later extended to framework for formal analysis of dependencies among services [69].

The theory of processes extending the FOCUS framework was introduced in [53]. This theory was further extended to have a formal model of processes that is compatible with the component/data flow view, cf. [60] [71]. In many cases, it is beneficial to specify on the same abstraction level not only system components but also processes within the system, however, if we have to apply different frameworks to analyse both views, the system model becomes hard to read and to understand. The presented in [71] approach provides a solution how to cover this gap and to reconcile component and process views.

6 CASE STUDIES

The summaries of the first case studies in FOCUS was presented approx. 25 years ago, in 1992 and 1994, cf. [18] [21]. The second summary was presented 5 years later, in 1997 [17].

Specification and refinement of a buffer of length one was presented in [10]. The first version of the FOCUS specification for a steam boiler system was introduced in [24].

A Trading System case study was used as common example for modelling approaches of component-based systems within the CoCoME contest to compare software component models. Broy et al. presented within this contest a systematic model-based approach of the engineering of distributed systems, which was based on the application of FOCUS and AutoFocus2, cf. [20]. The authors provide tool support around the AutoFocus2 tool, that enables us to execute our specified models in a distributed environment targeted to the CoCoME example.

Formal FOCUS specifications of FlexRay and FTCom were introduced in [48] [38] [39], where FlexRay is a time-triggered communication protocol, and FTCom is the communication layer of a time-triggered operating system OSEK-time. An operating system OSEKtime was developed by the European Automotive Consortium OSEK/VDX in accordance to the time-triggered paradigm. OSEK is a standards body, founded by German automotive company consortium, which included many industrial partners (e.g., BMW,
Bosch, Siemens, etc.) as well as the University of Karlsruhe. The French automotive manufacturers Renault and PSA Peugeot Citroen had a similar consortium, VDX. In 1994, a new consortium OSEK/VDX was created, based on OSEK and VDX. FlexRay and FTCom were introduced for the fault-tolerant communication by the FlexRay Consortium and OSEK/VDX respectively. Authors presented Focus specifications of FlexRay and FTCom that allow us to argue about the properties of FlexRay and FTCom in a formal manner. The Focus specification of FlexRay was also verified methodology “Focus on Isabelle”, discussed in Section 5, confirming that this specification of FlexRay fulfils the FlexRay requirements, cf. [45]. A number of case studies on the modelling of autonomous systems were presented in [74, 75, 78].

Within the methodology “Focus on Isabelle”, three case studies were elaborated using the version of Isabelle framework of 2007:

- data transmission (FlexRay communication protocol),
- process control (Steam Boiler System),
- memory and processing components (Automotive-Gateway System).

These case studies were later conducted using the Isabelle version of 2012, which allows to use the Isar language providing human-readable proofs in HOL, cf. [59]. A further optimisation of the case studies on the verification level was proposed in [74]: the authors introduced a human-oriented methodology for analysis of the dependencies between lemmas within the provided set of proofs, extending the “Focus on Isabelle” methodology.

The case study introduced in [60], presents a Focus formalisation of the security property of data secrecy along with the corresponding definitions and Isabelle/HOL proofs.

Böhm et al. [1] reported successful results of a project conducted in collaboration between Siemens AG, fortiss GmbH and TU Munich. The goal was to evaluate SPES modeling framework (SPES MF) implemented within AF3. Böhm et al. performed a case study, on modelling of requirements and functionality for a part of a Siemens train automation system. The results demonstrated advantages of application the SPES MF and AF3 within this context.

Campetelli et al. [28] presented an industrial case study from the automation domain, focusing on the control software components: a case example of a seawater desalination plant was modelled in AF3 according to the proposed SPES development method.

Spichkova et al. [79] illustrated using formal models for intelligent speed validation and adaptation. Formal specification of Chimney platform [93, 94], which provides a reliable computing and data management service, as well as its refinements and extensions were presented in [80, 72, 73].

Zamansky et. al. [95] reviewing some recent large-scale industrial projects in which formal methods (including Focus and AutoFocus) have been successfully applied. The authors also covered some aspects of teaching formal methods for software engineering, including Focus and AutoFocus, cf. [81, 44].

7 HUMAN-ORIENTED ASPECTS

Schätz et al. [43] argued almost 20 years ago that that formal techniques are indeed useful for practical application, but they should be put to indirect use. To demonstrate this approach, the authors analysed two pragmatic graphical description techniques, taken from the field of telecommunication. The analysis was targeting on the information content of the techniques and their application in the process of specification development. The authors defined the techniques formally, and introduced based on these formal definitions a number of development steps and their graphical counterparts. This work can be seen as the first step towards graphical specification style within the Focus framework as well as to the AutoFocus tool.

An approach presented in [56, 58] aims to apply the engineering psychology achievements to the design of formal methods, focusing on the specification phase of a system development process. Its core ideas originated from the analysis of the Focus framework and also led to an extended version of the framework, FocusST.

[58] introduced an research on incorporation of the human factors engineering into the software development process: The authors proposed to apply the human factors analysis not only the level of requirements specification and formal system modelling, but also to guide various testing tasks.
8 CONCLUSIONS

This paper provides a literature review of the methodological approaches, academic case studies and industrial applications of FOCUS and FOCUSST, the framework for formal specification and development of interactive systems, as well as the AF3 (AutoFocus 3) modelling tool developed based on the FOCUS theory.

Focus was introduced approx. 25 years ago, and extensively used since then in many academic and industrial projects. The literature review covers more than 80 publications on FOCUS, FOCUSST and AutoFocus research, from 1992 when the first publication on FOCUS appeared till 2017.

REFERENCES

[1] N. Alzahrani, M. Spichkova, and J. O. Blech. Spatio-temporal models for formal analysis and property-based testing. In Federation of International Conferences on Software Technologies: Applications and Foundations, pages 196–206. Springer, 2016.

[2] N. Alzahrani, M. Spichkova, and J. O. Blech. From temporal models to property-based testing. In 11th International Conference on Evaluation of Novel Approaches to Software Engineering (ENASE), pages 241–246. SCITEPRESS, 2017.

[3] V. Aravantinos, S. Voss, S. Teufl, F. Hözl, and B. Schätz. AutoFOCUS 3: Tooling Concepts for Seamless, Model-based Development of Embedded Systems. In ACES-MB, pages 19–26, 2015.

[4] W. Böhm, M. Junker, A. Vogelsang, S. Teufl, R. Pinger, and K. Rahn. A formal systems engineering approach in practice: An experience report. In Proceedings of the 1st International Workshop on Software Engineering Research and Industrial Practices, pages 34–41. ACM, 2014.

[5] J. Botaschanjan, M. Broy, A. Gruler, A. Harhurin, S. Knapp, L. Kof, W. Paul, and M. Spichkova. On the correctness of upper layers of automotive systems. Formal aspects of computing, 20(6):637–662, 2008.

[6] J. Botaschanjan, A. Gruler, A. Harhurin, L. Kof, M. Spichkova, and D. Trachtenherz. Towards modularized verification of distributed time-triggered systems. In Int. Symposium on Formal Methods, pages 163–178. Springer, 2006.

[7] J. Botaschanjan, L. Kof, C. Künnel, and M. Spichkova. Towards verified automotive software. In ACM SIGSOFT Software Engineering Notes, volume 30, pages 1–6. ACM, 2005.

[8] J. D. Brock and W. B. Ackerman. Scenarios: A model of non-determinate computation. In Formalization of programming concepts, pages 252–259. Springer, 1981.

[9] M. Broy. Advanced component interface specification. Theory and Practice of Parallel Programming, pages 369–392, 1995.

[10] M. Broy. Specification and refinement of a buffer of length one. In Deductive program design. NATO ASI Series, Series F: Computer and Systems Sciences. Vol. 152. Springer, 1995.

[11] M. Broy. Compositional refinement of interactive systems. ACM, 44(6):850–891, 1997.

[12] M. Broy. Towards a mathematical concept of a component and its use. Software-concepts and tools, 18(3):137, 1997.

[13] M. Broy. A logical basis for component-based systems engineering. In Calculational System Design. IOS Press, 1999.

[14] M. Broy. Time, Abstraction, Causality and Modularity in Interactive Systems: Extended Abstract. Electr. Notes Theor. Comput. Sci., 108:3–9, 2004.

[15] M. Broy. Service-oriented Systems Engineering: Specification and design of services and layered architectures. The JANUS Approach. Engineering Theories of Software Intensive Systems, pages 47–81, 2005.

[16] M. Broy. Structured modeling and specification of functional requirements. Science of Computer Programming, 75(12):1193–1214, 2010.

[17] M. Broy, M. Breitling, B. Schätz, and K. Spies. Summary of case studies in focus: A design method for distributed systems. Technische Universität München, Tech. Rep., 19740, 1997.

[18] M. Broy, F. Dederichs, C. Dendorfer, M. Fuchs, T. Gritzner, and R. Weber. Summary of case studies in focus: A design method for distributed systems. Technische Universität München, Tech. Rep., 9203, 1992.

[19] M. Broy, F. Dederichs, C. Dendorfer, M. Fuchs, T. F. Gritzner, and R. Weber. The design of distributed systems: an introduction to Focus. Technische Universität München, Tech. Rep., 9202, 1992.

[20] M. Broy, J. Fox, F. Hözl, D. Koss, M. Kuhrmann, M. Meisinger, B. Penzenstadler, S. Rittmann, B. Schätz, M. Spichkova, and D. Wild. Service-Oriented Modeling of CoCoME with Focus and AutoFocus. pages 177–206, 2008.

[21] M. Broy, M. Fuchs, T. Gritzner, B. Schätz, and K. S. Katharina Spies. Summary of case studies in focus: A design method for distributed systems. Technische Universität München, Tech. Rep., 9423, 1994.
\[\text{[22]}\ M.\ Broy,\ F.\ Huber,\ and\ B.\ Schätz.\ \textit{AutoFocus – Ein Werkzeugprototyp zur Entwicklung einge-}
\text{betterter Systeme. Informatik-Forschung und Ent-}
\text{wicklung, 14(3):121–134, 1999.}
\[\text{[23]}\ M.\ Broy,\ I.\ H.\ Krüger,\ and\ M.\ Meisinger. A formal model of services. \textit{ACM Trans. Softw. Eng. Methodol.}, 16(1), Feb. 2007.
\[\text{[24]}\ M.\ Broy,\ F.\ Regensburger,\ B.\ Schätz,\ and\ K.\ Spies. The Steamboiler Specification – A Case Study in Focus. \textit{Technische Universität München, Tech. Rep.}, 9022, 1992.
\[\text{[25]}\ M.\ Broy\ and\ K.\ Stølen. Specification and re-}
\text{finement of finite dataflow networks – a relational approach. In \textit{Formal Techniques in Real-Time and Fault-Tolerant Systems}, pages 247–}
\text{267. Springer, 1994.}
\[\text{[26]}\ M.\ Broy\ and\ K.\ Stølen. \textit{Specification and De-}
\text{velopment of Interactive Systems: Focus on Streams, Interfaces, and Refinement}. Springer, 2001.
\[\text{[27]}\ A.\ Campetelli,\ F.\ Hözl,\ and\ P.\ Neubeck. User-
\text{friendly model checking integration in model-
\text{based development. \textit{The International Society for Computers and Their Applications}}, 2011.
\[\text{[28]}\ A.\ Campetelli,\ M.\ Junker, B.\ Böhm, M.\ Da-
\text{vidich, V.\ Koutsoumpas, X.\ Zhu, and J.\ C.\ Wehrstedt. A model-based approach to formal verification in early development phases: A de-
\text{salination plant case study. In \textit{Software Engineering}}, pages 91–100, 2015.
\[\text{[29]}\ A.\ Cimatti\ and\ S.\ Tonetta. A temporal logics ap-
\text{proach to contract-based design. In \textit{Architecture-
\text{Centric Virtual Integration (ACVI)}}, pages 1–3. }
\text{IEEE, 2016.}
\[\text{[30]}\ S.\ Dobi,\ M.\ Gleirscher,\ M.\ Spichkova,\ and P.\ Struss. Model-based hazard and impact anal-
\text{ysis. \textit{arXiv preprint arXiv:1512.02759}}, 2015.
\[\text{[31]}\ M.\ Feilkas,\ A.\ Fleischmann,\ F.\ Hözl, C.\ Pfaller, K.\ Scheidemann,\ M.\ Spichkova,\ and D.\ Trachten-}
\text{henerz. A top-down methodology for the develop-
\text{ment of automotive software. \textit{Technische Uni-
\text{versität München, Tech. Rep.}}, 902, 2009.}
\[\text{[32]}\ M.\ Feilkas,\ F.\ Hözl, C.\ Pfaller, S.\ Rittmann, B.\ Schätz, W.\ Schwitzer, W.\ Sitou, M.\ Spichkova,\ and D.\ Trachten-}
\text{henerz. A Refined Top-Down Methodology for the Develop-
\text{ment of Automotive Software Systems – The KeylessEntry System Case Study. \textit{Technische Universität München, Tech. Rep.}}, 1103, 2011.
\[\text{[33]}\ F.\ Hözl\ and\ M.\ Feilkas. \textit{AutoFocus 3 – a scientific tool prototype for model-based development of component-based, reactive, distributed systems. In \textit{Model-Based Engineering of Embedded Real-Time Systems}}, pages 317–322. Springer, 2010.
\[\text{[34]}\ F.\ Hözl,\ M.\ Spichkova,\ and\ D.\ Trachten-}
\text{henerz. \textit{AutoFocus Tool Chain. \textit{Technische Universität München, Tech. Rep.}}, (TUM-I1021), 2010.
\[\text{[35]}\ F.\ Hözl,\ M.\ Spichkova,\ and\ D.\ Trachten-}
\text{henerz. Safety-critical system development methodology. \textit{Technische Universität München, Tech. Rep.}, (1020), 2010.
\[\text{[36]}\ S. Kanav and V. Aravantinos. Modular transformation from af3 to nuxmv. In \textit{MoDeVVa 2017. CEUR}, 2017.
\[\text{[37]}\ A. Kondeva, D. Ratiu, B. Schätz, and S. Voss. Seamless model-based development of embedded systems with AF3 phoenix. In \textit{Engineering of Computer Based Systems (ECBS)}, pages 212–}
\text{212. IEEE, 2013.}
\[\text{[38]}\ C.\ Kühnel\ and\ M.\ Spichkova. \textit{FlexRay und FTCom: Formale Spezifikation in FOCUS. \textit{Technische Universität München, Tech. Rep. I}}, 601:2006, 2006.
\[\text{[39]}\ C.\ Kühnel\ and\ M.\ Spichkova. Upcoming auto-
\text{matic standards for fault-tolerant communication: FlexRay and OSEKtime FTCom. In \textit{EFTS 2006 International Workshop on Engineering of Fault Tolerant Systems. Université du Luxembourg, CSC, Computer Science and Communi-
\text{cation}, 2006.}
\[\text{[40]}\ C.\ Kühnel\ and\ M.\ Spichkova. Fault-tolerant communication for distributed embedded sys-
\text{tems. In \textit{Software Engineering of Fault Toler-
\text{ance Systems (Series on Software Engineering and Knowledge Engineering)}}, volume 19, page 175. World Scientific Publishing, 2007.
\[\text{[41]}\ T. Niapkow, L. C. Paulson, and M. Wenzel. \textit{Isabelle/HOL – A Proof Assistant for Higher-
\text{Order Logic}}, volume 2283 of \textit{LNCS}. Springer, 2002.
\[\text{[42]}\ J. Philippus and B. Rumpe. Stepwise refine-
\text{ment of data flow architectures. \textit{arXiv preprint arXiv:1409.7247}}, 2014.
\[\text{[43]}\ B. Schätz, H. Hußmann, and M. Broy. Graphical development of consistent system specifications. In \textit{FME’96: Industrial Benefit and Advances In Formal Methods}, pages 248–267. Springer, 1996.
\[\text{[44]}\ M. Simic, M. Spichkova, H. Schmidt, and I. Peake. Enhancing learning experience by collabora-
\text{tive industrial projects. In \textit{ICEER 2016}, pages 1–8. Western Sydney University, 2016.
\[\text{[45]}\ M. Spichkova. \textit{FlexRay: Verification of the FOCUS Specification in Isabelle/HOL. A Case Study. \textit{Technische Universität München, Tech. Rep.}}, (602), 2006.
\[\text{[46]}\ M. Spichkova. Specification and Seamless Verif-
\text{ication of Embedded Real-Time Systems: FOCUS on Isabelle. PhD thesis, TU München, 2007.}
\[\text{[47]}\ M. Spichkova. Focus on isabelle: From specifi-
\text{cation to verification. \textit{Department of Electrical and Computer Engineering, Concordia Univer-
\text{sity, Tech. Rep.}}, 2008.
\[\text{[48]}\ M. Spichkova. Refinement-based verification of interactive real-time systems. \textit{Electronic Notes}
M. Spichkova, J. Blech, P. Herrmann, and H. Schmidt. Modeling spatial aspects of safety-critical systems with FocusST. In Mod-eVdA2014, pages 49–58. CEUR, 2014.

M. Spichkova and A. Campetelli. Towards system development methodologies: From software to cyber-physical domain. In First International Workshop on Formal Techniques for Safety-Critical Systems (FTSCS’15), 2012.

M. Spichkova, F. Hözl, and D. Trachtenherz. Verified system development with the autofocus tool chain. In 2nd Workshop on Formal Methods in the Development of Software (WS-FMDS 2012), volume 86, pages 17–24. Electronic Proceedings in Theoretical Computer Science, 2012.

M. Spichkova and J. Jürjens. Formal specification of cryptographic protocols and their composition properties: Focus-oriented approach. Technical report, Technische Universität München, 2008.

M. Spichkova, H. Liu, M. Laali, and H. W. Schmidt. Human factors in software reliability engineering. In Workshop on Applications of Human Error Research to Improve Software Engineering (WAHESE2015), 2015.

M. Spichkova and H. Schmidt. Towards logical architecture and formal analysis of dependencies between services. In The 2014 Asia-Pacific Services Computing Conference, 2014.

M. Spichkova and H. Schmidt. Formal-based framework for analysis of logical architecture. International Journal of Services Computing (IJISC), 3(3):1–15, 2015.

M. Spichkova and H. Schmidt. Reconciling a component and process view. 7th International Workshop on Modeling in Software Engineering (MiSE) at ICSE 2015, 2015.

M. Spichkova, H. Schmidt, I. E. Thomas, I. I. Yusuf, S. G. Androulakis, and G. R. Meyer. Managing usability and reliability aspects in cloud computing. In 11th International Conference on Evaluation of Novel Approaches to Software Engineering, pages 288–295, 2016.

M. Spichkova, H. W. Schmidt, I. I. Yusuf, I. E. Thomas, S. Androulakis, and G. R. Meyer. Towards modelling and implementation of reliability and usability features for research-oriented cloud computing platforms. In Evaluation of Novel Approaches to Software Engineering, Series on Communications in Computer and Information Science, pages 158–178. Springer, 2017.

M. Spichkova and M. Simic. Towards formal modelling of autonomous systems. In Intelligent Interactive Multimedia Systems and Services, pages 279–288. Springer, 2015.

M. Spichkova and M. Simic. Autonomous systems research embedded in teaching. In Intelligent Interactive Multimedia Systems and Services, pages 268–277. Springer, 2017.

M. Spichkova and M. Simic. Human-centred analysis of the dependencies within sets of
proofs. In *Knowledge-Based and Intelligent Information & Engineering Systems*, pages 2290–2298. Elsevier, 2017.

[77] M. Spichkova, M. Simic, and H. Schmidt. Formal model for intelligent route planning. *Procedia Computer Science*, 60:1299–1308, 2015.

[78] M. Spichkova, M. Simic, and H. Schmidt. From automotive to autonomous: Time-triggered operating systems. In *Intelligent Interactive Multimedia Systems and Services 2016*, pages 347–359. Springer, 2016.

[79] M. Spichkova, M. Simic, H. Schmidt, J. Cheng, X. Dong, Y. Gür, Y. Liang, P. Ling, and Z. Yin. Formal models for intelligent speed validation and adaptation. *Procedia Computer Science*, 96:1609–1618, 2016.

[80] M. Spichkova, I. Thomas, H. Schmidt, I. Yusuf, D. Drumm, S. Androulakis, G. Opletal, and S. Russo. Scalable and fault-tolerant cloud computations: Modelling and implementation. In 21st IEEE International Conference on Parallel and Distributed Systems, 2015.

[81] M. Spichkova and A. Zamansky. Teaching formal methods for software engineering. In *ENASE 2016*, pages 370–376. Science and Technology Publications, 2016.

[82] M. Spichkova, X. Zhu, and D. Mou. Do we really need to write documentation for a system? In *International Conference on Model-Driven Engineering and Software Development (MODELSWARD’13)*, 2013.

[83] M. Spivey. Understanding Z – A Specification Language and Its Formal Semantics. Cambridge Tracts in Theoretical Computer Science 3. Camb. Univ. Press, 1988.

[84] M. Spivey. The Z Notation: A Reference Manual, 2. Ausgabe. Prentice-Hall International Series in Computer Science. Prentice-Hall, 1992.

[85] K. Stelen. Using relations on streams to solve the rpc-memory specification problem. *Formal Systems Specification*, pages 477–520, 1996.

[86] S. Teufl, D. Mou, and D. Ratiu. Mira: A tooling-framework to experiment with model-based requirements engineering. In *Requirements Engineering Conference (RE), 2013 21st IEEE International*, pages 330–331. IEEE, 2013.

[87] P. Vo and M. Spichkova. Model-based generation of natural language specifications. *Software Technologies: Applications and Foundations*, (Human-Oriented Formal Methods), 2016.

[88] A. Vogelsang, S. Eder, G. Hackenberg, M. Junker, and S. Teufl. Supporting concurrent development of requirements and architecture: A model-based approach. In *Model-Driven Engineering and Software Development*, pages 587–595. IEEE, 2014.

[89] S. Voss and B. Schätz. Scheduling shared memory multicore architectures in AutoFocus 3 using Satisfiability Modulo Theories. In *Modellbasierte Entwicklung eingebetteter Systeme*, page 49, 2012.

[90] S. Voss and B. Schätz. Deployment and scheduling synthesis for mixed-critical shared-memory applications. In *Engineering of Computer Based Systems*, pages 100–109. IEEE, 2013.

[91] M. Walicki and M. Broy. Structured specifications and implementation of nondeterministic data types. *Technische Universität München, Tech. Rep.*, 9442, 1995.

[92] M. Wenzel. The Isabelle/Zar Reference Manual. [http://isabelle.in.tum.de/doc/isar-ref.pdf](http://isabelle.in.tum.de/doc/isar-ref.pdf) 2016.

[93] I. Yusuf, I. Thomas, M. Spichkova, S. Androulakis, G. Meyer, D. Drumm, G. Opletal, S. Russo, A. Buckle, and H. Schmidt. Chiminey: Reliable computing and data management platform in the cloud. In *International Conference on Software engineering*, pages 677–680, 2015.

[94] I. I. Yusuf, I. E. Thomas, M. Spichkova, and H. W. Schmidt. Chiminey: Connecting scientists to hpc, cloud and big data. *Big Data Research*, 8:39–49, 2017.

[95] A. Zamansky, G. Rodriguez-Navas, M. Adams, and M. Spichkova. Formal methods in collaborative projects. In *11th International Conference on Evaluation of Novel Approaches to Software Engineering*. IEEE, 2016.