RESEARCH CENTRE

Inria Centre at Université Côte d'Azur

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2024

ACTIVITY REPORT

Project-Team

KAIROS

Multiform Logical Time for Formal Cyber-Physical System Design

IN COLLABORATION WITH: Laboratoire informatique, signaux systèmes de Sophia Antipolis (I3S)

DOMAIN

Algorithmics, Programming, Software and Architecture

THEME

Embedded and Real-time Systems

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Project-Team KAIROS

Creation of the Project-Team: 2019 July 01

Keywords

Computer sciences and digital sciences

A1.1.1. – Multicore, Manycore

A1.1.2. – Hardware accelerators (GPGPU, FPGA, etc.)

A1.2.5. – Internet of things

A1.2.7. – Cyber-physical systems

A1.5.2. – Communicating systems

A2.2. – Compilation

A2.3. – Embedded and cyber-physical systems

A2.4. – Formal method for verification, reliability, certification

A2.5.1. – Software Architecture & Design

Other research topics and application domains

B5.1. – Factory of the future

B5.4. – Microelectronics

B6.1. – Software industry

B6.4. – Internet of things

B6.6. – Embedded systems

B6.7. – Computer Industry (harware, equipments...)

B7.2. – Smart travel

B8.1. – Smart building/home

B8.2. – Connected city

B9.5.1. – Computer science

1 Team members, visitors, external collaborators

Research Scientists

- Robert De Simone [Team leader, INRIA, Senior Researcher, until May 2024, HDR]
- Robert De Simone [Team leader, INRIA, Emeritus, from May 2024, HDR]
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Faculty Members

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- Julien DeAntoni [UNIV COTE D'AZUR, Associate Professor, until Apr 2024, HDR]
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- Joao Cambeiro [UNIV COTE D'AZUR (funded until Sept 2023)]
- Barbara Da Silva Oliveira [UNIV COTE D'AZUR]
- Arseniy Gromovoy [UNIV COTE D'AZUR, until Nov 2024]
- Maksym Labzhaniia [UNIV COTE D'AZUR]
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- Enlin Zhu [UNIV COTE D'AZUR, until Jun 2024]

Technical Staff

- Luc Hogie [CNRS, Engineer]

Interns and Apprentices

- Khadija Bendib [UNIV COTE D'AZUR, Intern, from Jun 2024 until Aug 2024]
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- Thomas Gorisse [INSA LYON, Intern, from Jul 2024 until Sep 2024]
- Rayane Larbi [IUT NICE, Intern, from May 2024 until Jul 2024]
- Alex Ndouna [INRIA, Intern, from Jul 2024 until Nov 2024]
- Thomas Portelette [INRIA, Intern, from Apr 2024 until Jul 2024]
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- Weishen Zou [UNIV COTE D'AZUR, Intern, from Jul 2024 until Sep 2024]

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- Patricia Riveill [INRIA]

Visiting Scientist

- Joelle Despeyroux [INRIA, until Jun 2024]

2 Overall objectives

The Kairos ambitions are to deal with the Design of Cyber-Physical Systems (CPS), at various stages, using Model-Based techniques and Formal Methods. Design here stands for co-modeling, co-simulation, formal verification and analysis activities, with connections both ways from models to code (synthesis and instrumentation for optimization). Formal analysis, in turn, concerns both functional and extra-functional correctness properties. Our goal is to link these design stages together, both vertically along the development cycle, and horizontally by considering the interactions between cyber/digital and physical models. These physical aspects comprise both physical environments and physical execution platform representations, which may become rather heterogeneous as in the cases of the Internet of Things (IoT) and computing at the edges of the gateways. The global resulting methodology can be tagged as Model-Based, Platform-Based CPS Design, see Figure 1.

CPS design must take into account all 3 aspects of application requirements, execution platform guarantees and contextual physical environment to establish both functional and temporal correctness. The general objective of Kairos is thus to contribute in the definition of a corresponding design methodology, based on formal Models of Computation for joint modeling of cyber and physical aspects, and using the important central concept of Logical Time for expressing the requirements and guarantees that define CPS constraints.

Logical Multiform Time. It may be useful to provide an introduction and motivation for the notion of Logical Multiform Time (and Logical Clocks), as they play a central role in our approach to Design. We call Logical Clock any repetitive sequence of occurrences of an event (disregarding possible values carried by the event). It can be regularly linked to physical time (periodic), but not necessarily so: fancy processors may change speeds, simulation engine change time-integration steps, or much more generally one may react with event-driven triggers of complex logical nature (do this after 3-times that unless this...). It is our belief that user specifications are generally expressed using such notions, with only partial timing correlations between distinct logical clocks, so that the process of realization (or "model-based compilation") consists for part in establishing (by analysis or abstract simulation) the possible tighter relations between those clocks (unifying them from a partial order of local total orders to a global total order).

Kairos defined in the past a small language of primitives expressing recognized constraints structuring the relations between distinct logical clocks [1, 7]. This language (named CCSL for Clock Constraint Specification Language), borrows from notions of Synchronous Reactive Languages [9], Real-Time Scheduling

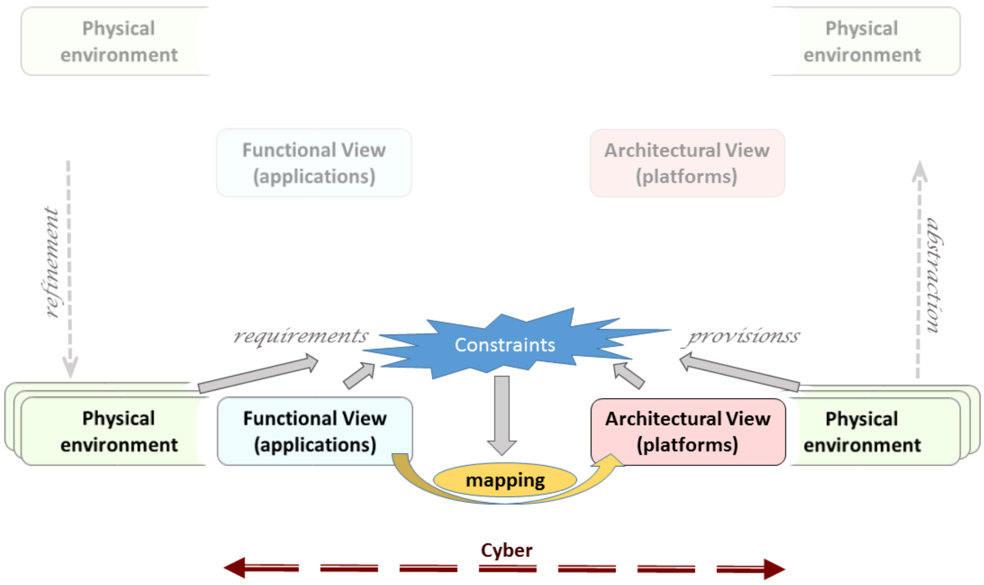

Figure 1: Cyber-Physical generic architectural features

Theory, and Concurrent Models of Computations and Communication (MoCCs) in Concurrency Theory [8] altogether. Corresponding extensions of Timed Models originally based on single (discrete or continuous) time can also be considered. Logical Time is used in our approach to express relation constraints between heterogeneous models, of cyber or physical origin, and to support analysis and co-simulation. Addressing cyber-physical systems demands to revisit logical time to deal with the multi-physical and sometimes uncertain environments.

Kairos is also active in Standardisation of the above mentioned Cyber-Physical Systems, in Internet of Things, and in Smart Contracts languages for electronic ledgers.

3 Research program

3.1 Cyber-Physical co-modeling

In Real-Time embedded systems, timing criticality imposes to take time predictivity as much into account as functional determinism, and this from the very beginning design phases onward. In addition, cyber-Physical System modeling requires joint representation of digital/cyber controllers and natural physics environments. Heterogeneous modeling must then be articulated to support accurate (co-)simulation, (co-)analysis, and (co-)verification, with multiple logical time sources and scales.

Figure 1 sketches the overall design framework. It comprises functional requirements, to be met provided surrounding platform guarantees, in a contract approach. All relevant aspects are modeled with proper Domain Specific Languages (DSL), so that constraints can be gathered globally, then analyzed to build a mapping proposal with both a structural aspect (functions allocated to platform resources), but also behavioral ones, scheduling activities. Mapping may be computed automatically or not, provably correct or not, obtained by static analytic methods or abstract execution.

Physical phenomena (in a very broad acceptance of the term) are usually modeled using continuous-time models and differential equations. Then the “proper” discretization opportunities for numerical simulation form a large spectrum of mathematical engineering practices. Note that, this is not at all the domain of expertise of Kairos members, but it should not be a limitation as long as one can assume a number of properties from the discretized version. On the other hand, we do have a strong expertise on modeling of both embedded processing architectures and embedded software (i.e., the kind of usually concurrent, sometimes distributed software that reacts to and control the physical environment). This is important as, unlike in the "physical" areas where modeling is common-place, modeling of software and programs is far from mainstream in the Software Engineering community. These domains are also an area of computer science where modeling, and even formal modeling, of the real objects that are originally of discrete/cyber nature, takes some importance with formal Models of Computation and Communications. It seems therefore quite natural to combine physical and cyber modeling in a more global design approach (even multi-physic domains and systems of systems possibly, but always with software-intensive aspects involved).

Our objective is certainly not to become experts in physical modeling and/or simulation process, but to retain from it only the essential and important aspects to include them into System-Level Engineering design, based on Model-Driven approaches allowing formal analysis (see for example the injection of formal semantics into the Capella System Engineering tool).

This sets an original research agenda: Model-Based System Engineering environments exist, at various stages of maturity and specificity, in the academic and industrial worlds. Formal Methods and Verification/Certification techniques also exist, but generally in a point-wise fashion. Our approach aims at raising the level of formality describing relevant features of existing individual models, so that formal methods can have a greater general impact on usual, "industrial-level", modeling practices. Meanwhile, the relevance of formal methods is enhanced as it now covers various aspects in a uniform setting (timeliness, energy budget, dependability, safety/security...).

Directions on formalizing CPS should focus on the introduction of uncertainty (stochastic models) in our particular framework, on relations between (logical) real-time and security, and on accounting for resource discovery also in presence of mobility inherent to connected objects and Internet of Things [2].

3.2 Cyber-Physical co-simulation

The FMI standard (Functional Mock-Up Interface) has been proposed for "purely physical" (i.e., based on persistent signals) co-simulation, and then adopted in over 100 industrial tools including frameworks such as Matlab/Simulink and Ansys, to mention two famous model editors. With the recent use of co-simulation to cyber-physical systems, dealing with the discrete and transient nature of cyber systems became mandatory.

Together with other people from our community, we showed that FMI and other frameworks for co-simulation badly support co-simulation of cyber-physical systems; leading to bad accuracy and performances. More precisely, the way to interact with the different parts of the co-simulation require a specific knowledge about its internal semantics and the kind of data exposed (e.g., continuous, piecewise-constant). Towards a better co-simulation of cyber-physical systems, we are looking for conservative abstractions of the parts and formalisms that aim to describe the functional and temporal constraints that are required to bind several simulation models together.

3.3 Formal analysis and verification

Because the nature of our constraints is specific, we want to adjust verification methods to the goals and expressiveness of our modeling approach [12]. Quantitative (interval) timing conditions on physical models combined with (discrete) cyber modes suggest the use of SMT (Satisfiability Modulo Theories) automatic solvers, but the natural expressiveness requested (as for instance in our CCSL constructs) shows this is not always feasible. Either interactive proofs, or suboptimal solutions (essentially resulting of abstract run-time simulations) should be considered.

Complementarily to these approaches, we are experimenting with new variants of symbolic behavioral semantics, allowing to construct finite representations of the behavior of CPS systems with explicit handling of data, time, or other non-functional aspects [4].

3.4 Relation between model and code

While models considered in Kairos can also be considered as executable specifications (through abstract simulation schemes), they can also lead to code synthesis and deployment. Conversely, code execution of smaller, elementary software components can lead to performance estimation enriching the models before global mapping optimization [3].

CPS introduce new challenging problems for code performance stability. Indeed, two additional factors for performance variability appear, which were not present in classical embedded systems: 1) variable and continuous data input from the physical world and 2) variable underlying hardware platform. For the first factor, CPS software must be analyzed in conjunction with its data input coming from the physics, so the variability of the performance may come from the various data. For the second factor, the underlying hardware of the CPS may change during the time (new computing actors appear or disappear, some actors can be reconfigured during execution). The new challenge is to understand how these factors influence performance variability exactly, and how to provide solutions to reduce it or to model it. The modeling of performance variability becomes a new input.

3.5 Code generation and optimization

A significant part of CPS design happens at model level, through activities such as model construction, analysis, or verification. However, in most cases the objective of the design process is implementation. We mostly consider the implementation problem in the context of embedded, real-time, or edge computing applications, which are subject to stringent performance, embedding, and safety *non-functional requirements*.

The implementation of such systems usually involves a mix of synthesis—(real-time) scheduling, code generation, compilation—and performance (*e.g.* timing) analysis, as introduced in [5]. One key difficulty here is that synthesis and performance analysis depend on each other. As enumerating the various solutions is not possible for complexity reasons, heuristic implementation methods are needed in all cases. One popular solution here is to build the system first using unsafe performance estimations for its components, and then check system *schedulability* through a global analysis. Another solution is to use safe, over-approximated performance estimations and perform their mapping in a way that ensures by construction the schedulability of the system.

In both cases, the level of specification for the compound design space -including functional application, execution platform, extra-functional requirements, implementation representation is a key problem. Another problem is the definition of scalable and efficient mapping methods based on both "exact" approaches (ILP/SMT/CP solving) and compilation-like heuristics.

3.6 Extensions for spatio-temporal modeling and mobile systems

While Time is clearly a primary ingredient in the proper design of CPS systems, in some cases, Space and related notions of local proximity or conversely long distance, play also a key role for correct modeling, often in part because of the constraints this puts on interactions and time for communications. Once space is taken into account, one has to recognize also that many systems will request to consider mobility, originated as change of location through time. Mobile CPSs (or mCPS) occur casually in real-life, e.g., in the case of Intelligent Transportation Systems, or roaming connected objects of the IoT.

Spatio-temporal and mobility modeling may each lead to dynamicity in the representation of constraints, with the creation-deletion-discovering of new components in the system. This opportunity for new expressiveness will certainly cause new needs in handling constraint systems and topological graph locations. The new challenge is to provide an algebraic support with a constraint description language that could be as simple and expressive as possible, and of use in the semantic annotations for mobile CPS design. We also aim to provide fully distributed routing protocols to manage Semantic Resource Discovery in IoT and to standardize it.

3.7 Towards foundations of synchronous languages

The challenge is to find new process algebras with deterministic dynamic semantics à la Plotkin (SOS) and decidable static semantics (types) able to specify the behavior of synchronous programming languages. The distinctive property of this evaluation strategy is to achieve determinacy-by-construction for multicast concurrent communication with shared memory. In particular, it permits us to model shared memory multi-threading with reaction to absence. This new theory lies at the core of the synchronous programming language Esterel. Adding types to such algebras would allow to certify them through *ad hoc* Interactive Theorem Provers (ITP) taking into account time, using our expertise acquired in [6, 10].

3.8 IoT and CPS standardization activities

Under the shield of the European Telecommunication Standard Institute (ETSI), we study protocols, languages, architectures, able to models and performances of widely used CPS, mCPS and IoT, with a particular care on IoT service discovery and direct applications in the domain of eHealth. We aim to experiment, with suitable proof-of-concepts and simulation software, and to evaluate performances and prototype applications, and we employ the Kairos theoretical and implementation skills to improve and make standards useful.

4 Application domains

4.1 Cyber-Physical and embedded system design

System Engineering for CPS systems requires combinations of models, methods, and tools owing to multiple fields, software and system engineering methodologies as well as various digitalization of physical models (such as "Things", in Internet of Things (IoT)). Such methods and tools can be academic prototypes or industry-strength offers from tool vendors, and prominent companies are defining design flow usages around them.

We have historical contacts with industrial and academic partners in the domains of avionics and embedded electronics (Airbus, Thales, Safran). We also have new collaborations in the fields of satellites (Thales Alenia Space) and connected cars driving autonomously (Renault Software Factory). These provide us with current use cases and new issues in CPS co-modeling and co-design (Digital Twins) further described in New Results section. The purpose here is to insert our formal methods into existing design flows, to augment their analysis power where and when possible.

4.2 Safe driving rules for automated driving

Self-driving cars will have to respect roughly the same safety-driving rules as currently observed by human drivers (and more). These rules may be expressed syntactically by temporal constraints (requirements and provisions) applied to the various meaningful events generated as vehicles interact with traffic signs, obstacles and other vehicles, distracted drivers and so on. We feel our formalisms based on Multiform Logical Time to be well suited to this aim, and follow this track in several collaborative projects with automotive industrial partners. This domain is an incentive to increase the expressiveness of our language and test the scalability of our analysis tools on real size data and scenari.

4.3 Smart Contracts specifications and standards

In collaboration with local industrial and international standardization partners, we have considered Smart Contracts (SC), as a way to formally establish specification of behavioral system traces, applied to connected objects in an IoT environment and the possibility to introduce a contract versioning electronic signature before the deployment in an electronic ledger.

The ANR project SIM (finished mid 2023) is based on the definition of formal language to describe services for autonomous vehicles that would execute automatically based on the observation of what is happening on the vehicle or the driver. The key focus is on the design of a virtual passport for autonomous cars that would register the main events occurring on the car and would use them to operate automatic but trustworthy and reliable services.

Building on our past expertise in the semantics of object-oriented programming languages (as referenced in [45]), the ETSI project STF655 (see contract section) aims to establish a "chain of trust." This trust mechanism is based on multiple entities, each of which will digitally sign the smart contract code. The resulting chain of signatures should enable the tracing of responsibility for every entity involved in the design, implementation, deployment, and execution of smart contracts.

We also investigate ways to extend smart contract languages and electronic ledgers with the capacity of modification/update, so creating some versioning facilities. Smart Contracts versioning would be particularly useful because logic or code can evolve during time for many reasons that cannot be stated at the time of deploying in a immutable electronic ledger.

4.4 IoT standards

Based on our skills in the "Internet" side of IoT, and in particular in content-based routing protocols, IoT Semantic Discovery Protocols [43, 42] and content-based network protocols [36, 40], we contribute to the ETSI Technical Committee Smart Machine-to-Machine Communications (TC SmartM2M) standards and the oneM2M Consortium in the following standardization enhancements:

- In the ETSI Test Task Force (TTF019) project (see contract section), we consider as performance evaluation, analysis, planning and deployment for some (but not all) open source implementations of oneM2M standard.
- In the ETSI Specialist Task Force (STF697) project (see contract section), we will consider extending the ETSI Asynchronous Contact Tracing protocol (TS 103757) as an overlay alertness network standard made of IoT devices, that can enable multiple detection and surveillance platforms to communicate and cooperate together.

5 Social and environmental responsibility

5.1 Footprint of research activities

- Julien Deantoni and Frédéric Mallet are members of the I3S Working Group on new practical ways to measure and reduce the impact of our research activity on the environment.
- Julien Deantoni is one of the organizer of the citizens' convention for the reduction of the carbon footprint of the I3S laboratory.
- Barbara Da Silva Oliveira and Marie-Agnès Peraldi-Frati were randomly selected and accepted to participate in the citizens' convention for reducing the carbon footprint of the I3S laboratory.

6 Highlights of the year

Frédéric Mallet, Professor and Director of the i3S Laboratory, was awarded the "insignes de chevalier dans l'ordre des Palmes académiques". This award celebrates the individuals newly appointed to the Order of the Academic Palms, one of the most prestigious civil distinctions in France, and recognizes members of the academic community for their exemplary commitment to the public service of education and their significant contributions to the international reputation of the University.

7 New software, platforms, open data

7.1 New software

7.1.1 TimeSquare

Keywords: Profil MARTE, Embedded systems, UML, IDM

Scientific Description: TimeSquare offers six main functionalities:

1) graphical and/or textual interactive specification of logical clocks and relative constraints between them, 2) definition and handling of user-defined clock constraint libraries, 3) automated simulation of concurrent behavior traces respecting such constraints, using a Boolean solver for consistent trace extraction, 4) call-back mechanisms for the traceability of results (animation

of models, display and interaction with waveform representations, generation of sequence diagrams...). 5) compilation to pure java code to enable embedding in non eclipse applications or to be integrated as a time and concurrency solver within an existing tool. 6) a generation of the whole state space of a specification (if finite of course) in order to enable model checking of temporal properties on it

Functional Description: TimeSquare is a software environment for the modeling and analysis of timing constraints in embedded systems. It relies specifically on the Time Model of the Marte UML profile, and more accurately on the associated Clock Constraint Specification Language (CCSL) for the expression of timing constraints.

URL: http://timesquare.inria.fr

Contact: Julien Deantoni

Participants: Benoit Ferrero, Charles Andre, Frédéric Mallet, Julien Deantoni, Nicolas Chleq

7.1.2 GEMOC Studio

Name: GEMOC Studio

Keywords: DSL, Language workbench, Model debugging

Scientific Description: The language workbench put together the following tools seamlessly integrated to the Eclipse Modeling Framework (EMF):

1) Melange, a tool-supported meta-language to modularly define executable modeling languages with execution functions and data, and to extend (EMF-based) existing modeling languages. 2) MoCCML, a tool-supported meta-language dedicated to the specification of a Model of Concurrency and Communication (MoCC) and its mapping to a specific abstract syntax and associated execution functions of a modeling language. 3) GEL, a tool-supported meta-language dedicated to the specification of the protocol between the execution functions and the MoCC to support the feedback of the data as well as the callback of other expected execution functions. 4) BCOoL, a tool-supported meta-language dedicated to the specification of language coordination patterns to automatically coordinates the execution of, possibly heterogeneous, models. 5) Monilog, an extension for monitoring and logging executable domain-specific models 6) Sirius Animator, an extension to the model editor designer Sirius to create graphical animators for executable modeling languages.

Functional Description: The GEMOC Studio is an Eclipse package that contains components supporting the GEMOC methodology for building and composing executable Domain-Specific Modeling Languages (DSMLs). It includes two workbenches: The GEMOC Language Workbench: intended to be used by language designers (aka domain experts), it allows to build and compose new executable DSMLs. The GEMOC Modeling Workbench: intended to be used by domain designers to create, execute and coordinate models conforming to executable DSMLs. The different concerns of a DSML, as defined with the tools of the language workbench, are automatically deployed into the modeling workbench. They parametrize a generic execution framework that provides various generic services such as graphical animation, debugging tools, trace and event managers, timeline.

URL: http://gemoc.org/studio.html

Publications: hal-00850770, hal-01355391, hal-01609576, hal-01651801, hal-01152342, hal-03374955, hal-01614561, hal-01616154

Contact: Benoît Combemale

Participants: Didier Vojtisek, Erwan Bousse, Julien Deantoni

Partners: I3S, Université de Nantes

7.1.3 Lopht

Name: Logical to Physical Time Compiler

Keywords: Real time, Compilation

Scientific Description: The Lopht (Logical to Physical Time Compiler) has been designed as an implementation of the AAA methodology. Like SynDEx, Lopht relies on off-line allocation and scheduling techniques to allow real-time implementation of dataflow synchronous specifications onto multi-processor systems. But there are several originality points: a stronger focus on efficiency, which results in the use of a compilation-like approach, a focus on novel target architectures (many-core chips and time-triggered embedded systems), and the possibility to handle multiple, complex non-functional requirements covering real-time (release dates and deadlines possibly different from period, major time frame, end-to-end flow constraints), ARINC 653 partitioning, the possibility to preempt or not each task, and finally SynDEx-like allocation.

Functional Description: Compilation of high-level embedded systems specifications into executable code for IMA/ARINC 653 avionics platforms. It ensures the functional and non-functional correctness of the generated code.

Contact: Dumitru Potop-Butucaru

Participants: Dumitru Potop-Butucaru, Manel Djemal, Thomas Carle, Zhen Zhang

7.1.4 LoPhT-manycore

Name: Logical to Physical Time compiler for many cores

Keywords: Real time, Compilation, Task scheduling, Automatic parallelization

Scientific Description: Lopht is a system-level compiler for embedded systems, whose objective is to fully automate the implementation process for certain classes of embedded systems. Like in a classical compiler (e.g. gcc), its input is formed of two objects. The first is a program providing a platform-indepedent description of the functionality to implement and of the non-functional requirements it must satisfy (e.g. real-time, partitioning). This is provided under the form of a data-flow synchronous program annotated with non-functional requirements. The second is a description of the implementation platform, defining the topology of the platform, the capacity of its elements, and possibly platform-dependent requirements (e.g. allocation).

From these inputs, Lopht produces all the C code and configuration information needed to allow compilation and execution on the physical target platform. Implementations are correct by construction. Resulting implementations are functionally correct and satisfy the non-functional requirements. Lopht-manycore is a version of Lopht targeting shared-memory many-core architectures.

The algorithmic core of Lopht-manycore is formed of timing analysis, allocation, scheduling, and code generation heuristics which rely on four fundamental choices. 1) A static (off-line) real-time scheduling approach where allocation and scheduling are represented using time tables (also known as scheduling or reservation tables). 2) Scalability, attained through the use of low-complexity heuristics for all synthesis and associated analysis steps. 3) Efficiency (of generated implementations) is attained through the use of precise representations of both functionality and the platform, which allow for fine-grain allocation of resources such as CPU, memory, and communication devices such as network-on-chip multiplexers. 4) Full automation, including that of the timing analysis phase.

The last point is characteristic to Lopht-manycore. Existing methods for schedulability analysis and real-time software synthesis assume the existence of a high-level timing characterization that hides much of the hardware complexity. For instance, a common hypothesis is that synchronization and interference costs are accounted for in the duration of computations. However, the high-level timing characterization is seldom (if ever) soundly derived from the properties of the platform and the program. In practice, large margins (e.g. 100%) with little formal justification are added to computation durations to account for hidden hardware complexity. Lopht-manycore overcomes this limitation. Starting from the worst-case execution time (WCET) estimations of computation operations and from a precise and safe timing model of the platform, it maintains a precise timing accounting throughout the mapping process. To do this, timing accounting must take into account all details of allocation, scheduling, and code generation, which in turn must satisfy specific hypotheses.

Functional Description: Accepted input languages for functional specifications include dialects of Lustre such as Heptagon and Scade v4. To ensure the respect of real-time requirements, Lopht-manycore pilots the use of the worst-case execution time (WCET) analysis tool (aiT from AbsInt, https://www.absint.com/ait/index.htm). By doing this, and by using a precise timing model for the platform, Lopht-manycore eliminates the need to adjust the WCET values through the addition of margins to the WCET values that are usually both large and without formal safety guarantees. The output of Lopht-manycore is formed of all the multi-threaded C code and configuration information needed to allow compilation, linking/loading, and real-time execution on the target platform.

Contact: Dumitru Potop-Butucaru

Participants: Dumitru Potop-Butucaru, Keryan Didier

7.1.5 mlirlus

Name: Lustre-based reactive dialect for MLIR

Keywords: Machine learning, TensorFlow, MLIR, Reactive programming, Real time, Embedded systems, Compilers

Scientific Description: We are interested in the programming and compilation of reactive, real-time systems. More specifically, we would like to understand the fundamental principles common to general-purpose and synchronous languages—used to model reactive control systems—and from this to derive a compilation flow suitable for both high-performance and reactive aspects of a modern control application. To this end, we first identify the key operational mechanisms of synchronous languages that SSA does not cover: synchronization of computations with an external time base, cyclic I/O, and the semantic notion of absent value which allows the natural representation of variables whose initialization does not follow simple structural rules such as control flow dominance. Then, we show how the SSA form in its MLIR implementation can be seamlessly extended to cover these mechanisms, enabling the application of all SSA-based transformations and optimizations. We illustrate this on the representation and compilation of the Lustre dataflow synchronous language. Most notably, in the analysis and compilation of Lustre embedded into MLIR, the initialization-related static analysis and code generation aspects can be fully separated from memory allocation and causality aspects, the latter being covered by the existing dominance-based algorithms of MLIR/SSA, resulting in a high degree of conceptual and code reuse. Our work allows the specification of both computational and control aspects of high-performance real-time applications. It paves the way for the definition of more efficient design and implementation flows where real-time ressource allocation drives parallelization and optimization.

Functional Description: The Multi-Level Intermediate Representation (MLIR) is a new reusable and extensible compiler infrastructure distributed with LLVM. It stands at the core of the back-end of the TensorFlow Machine Learning framework. mlirlus extends MLIR with dialects allowing the representation of reactive control needed in embedded and real-time applications.

Release Contributions: First open-source and public version.

URL: `https://github.com/dpotop/mlir-lus-public`

Publication: hal-03043623

Contact: Dumitru Potop-Butucaru

Partner: Google

7.1.6 Idawi

Keyword: Middleware

Functional Description: Idawi is a middleware for the development and experimentation of distributed applications for multi-hop dynamic networks, like the IoT, the Edge, Mobile Ad hoc Networks, etc. The development of Idawi was initially motivated by the need of the COATI Research group to deploy scientific applications in clusters of computers, in order to run large experimentation campaigns of graph algorithms. Idawi is an innovative arrangement of many features found in existing tools into a fresh Open Source Java reference implementation, but in our Research context we were led to introduce new ideas not found in other middleware solutions for distributed computing - such as a fully decentralized network model, and a by-default collective communication/computation model (both naturally matching the very nature of mobile multi-hop networks), the use of digital twins at the core of its network management model, as well as new features making it usable as a Research platform for the experimentation of middleware-level techniques. Idawi defines application elements as components organized into a multi-hop overlay network on top of agnostic transport layers such as TCP, UDP and SSH (SSH being employed to enable component deployment and communication even in the presence of NATs and firewalls). In the usual use case, there will be only one component per device. But, in order to enable the simulation/emulation of large systems, components can deploy other components in their Java Virtual Machine (JVM) or in another JVM(s) in the same device. Idawi proposes a structuring model of distributed applications, which then must conform to a specific Object-Oriented model in the style of SOA: it defines that components expose their functionality via services. Services hold data and implement functionality about the specific concern they are about. Functionality is then exposed via (optionally typed) endpoints, which can be triggered remotely from anywhere in the component overlay. Idawi features a multi-paradigm programming model. Messaging (and hence remote code invocation) can be both synchronous (imperative) and asynchronous (reactive/event-driven). It is powered by a default routing scheme and APIs that are tailored to collective communication, so as to offer native support for parallel processing. Idawi comes with a set of built-in fully decentralized services for automatized quick deployment/bootstrapping of components through SSH, interoperability through a REST-based web interface, service provisioning and discovery, overlay management, and many other system-level functionality.

URL: `https://github.com/lhogie/idawi`

Publications: hal-04878642, hal-03863333, hal-03886521, hal-03562184

Contact: Luc Hogie

7.1.7 ACT

Name: Asynchronous Contact Tracing Framework

Keywords: Contact tracing, Iot, Standards, Routing

Scientific Description: Implementation of standard ETSI TS 103757

Functional Description: ACT consists in 3 modules: 1) an ETSI/oneM2M communication infrastructure, 2) a mobile application (android), and 3) a web application.

Release Contributions: First open-source and public version available on gitlab inria

URL: `https://gitlab.inria.fr/act/`

Publications: hal-02989793, hal-02989404, hal-03127890, hal-03935906

Contact: Luigi Liquori

Participants: Thomas Gorisse, Luigi Liquori, Pascal Tempier, Enrico Scarrone

Partners: ETSI, Université Côte d'Azur (UCA)

8 New results

8.1 Logical Time for safety requirements in safety-critical systems

Participants: Frédéric Mallet, Pavlo Tokariev, Robert de Simone.

One of the main goals of Kairos is to show how logical time gives a flexible model of time that can be progressively refined from requirements down to the embedded code.

In [13], we show that we can detect insistencies in formal requirements by detecting *bad* patterns in the causality clock graphs. Contrary to our previous works, the efficiency does not come from a detailed analysis of the semantic models but rather we use the topology of the requirement models to filter out bad requirements. This was done in collaboration with our Chinese partners, mostly in the context of our associated-team Plot4IoT (see collaboration section).

In [15], we have pursued our previous work on dynamic logic. The idea is to deal jointly with the properties and the reactive program rather than only considering the properties to be verified. We use CCSL to capture the properties and a reactive language inspired from Esterel for the program. In this context, because of decidability issues, the proofs are not fully automatic. We look for ways to reduce the burden of the manual proofs.

Finally, in order to get closer to the requirements expressed in natural language, we have, in the context of the PhD of Pavlo Tokariev, proposed some syntactic extentions to CCSL. This new language, called MRT-CCSL [21], proposed some modular extensions as well as native constructs to deal with *real-time* requirements. Pavlo has defended his PhD on December 13th showing how these syntactic extensions open the path to using new semantic models based on abstract interpretation and polyedral libraries making some of the analysis tractable, even though not very efficient [26].

8.2 Safety rules for autonomous driving

Participants: Frédéric Mallet, Maksym Labzhaniia, Marie-Agnès Peraldi-Frati, Julien Deantoni, Robert de Simone.

We previously addressed the formal modeling of automotive driving Safety Rules in a prior PhD thesis [35]. In the current PhD work of Maksym Labzhaniia, we are revisiting this language in light of logical multi-dimensionality, particularly with respect to time and space (interconnected through speed). While we have published initial results on the formal spatio-temporal framework in [16], we are now exploring how this framework can be integrated with a Domain-Specific Language (DSL) on one hand, and with execution/simulation traces on the other. The ultimate goal is to develop a DSL through which scenarios can be validated, either offline or online, serving as an AI safety check.

8.3 Cyber Physical Systems co-Modeling and co-Simulation

Participants: Julien Deantoni, Nicolas Ferry, Barbara Da Silva Oliveira, Joao Cambeiro.

This research study illustrates how we leveraged lessons learned from previous work to make explicit the semantic relations between models of different natures. This year, the consideration of both simulation and operational model behaviors led us into the Digital Twin landscape, where three scientific questions have been addressed:

1. In Joao Cambeiro's PhD thesis (currently under final development), we investigated how to define and manage model fidelity to enable the selection of models as appropriate candidates for validating specific requirements. Additionally, we used such fidelity definitions to study its use in the engineering of Digital Twins.

2. We also studied the implicit influences in the behavior of heterogeneous models and how making them explicit can be leveraged to facilitate collaboration between various stakeholders during collaborative development activities [20]. These aspects are further explored in the ongoing PhD thesis of Barbara da Silva Oliveira.

3. Finally, we recently addressed how the hybridization of models from the operational phase in one hand and design/simulation phase on the other hand can improve the management of system uncertainty, leading to better control and drift management [27]

This activity may eventually merge with the one from section 8.2 since the goal is to consider heterogeneous models from different system life cycle activities.

8.4 Multi-core parallelization of safety-critical real-time applications

Participant: Dumitru Potop Butucaru.

This work involved a collaboration with Airbus and the Inria Parkas team (Tim Bourke).

We have continued our collaboration with Airbus and Safran aiming at safe and efficient multi-core implementation of avionics applications. We have designed and implemented optimal synchronization protocols for the generated code, we have further advanced in modeling and reducing inter-core interferences, we have further optimized the scheduling heuristics, and we have integrated our Lopht multi-core parallelizing back-end with the pressail front-end provided by the Inria Parkas team and the multi-core Lopht back-end.

Results: software Lopht, direct financing by Airbus.

8.5 Bidirectional Reactive Programming for Machine Learning

Participants: Dumitru Potop Butucaru.

This is a collaboration with Google DeepMind (Albert Cohen, Gordon Plotkin).

While Machine Learning (ML) algorithms are typically specified in Python, using libraries with rapidly-evolving syntax and semantics, their informal description follows a dataflow reactive form. Our contribution here is threefold:

- We determined that the 4 primitives statements of conventional dataflow reactive languages allow the representation of the control aspects of all layers and models (in both inference and training form) if they do not involve bidirectional propagation or batch normalization. The same primitives also allow representing the top-level drivers of supervised training and the reinforcement learning (RL) agents, and allow seamless integration with data pre- and post-processing. This grand unification paves the way for simpler, clearer specification and more efficient compilation of ML-based applications.

- We extended dataflow reactive programming with recurrences backward in time, which are needed to represent bidirectional layers (such as transformers), batch normalization, or the training of stateful networks by means of back-propagation through time. The resulting language allows the representation of all ML models working on data organized along a time dimension. Our extension preserves the bounded time and memory guarantees of reactive languages whenever recurrences backwards in time have a bounded horizon.
- We provide the formal semantics of this language. As recurrences backwards in time allow for causality cycles involving multiple time indices, we determine that, to ensure productivity (i.e. the absence of deadlocks), chains of backward dependences must always eventually terminate, so that execution can be implemented as globally forwards and locally backwards with finite buffering.

The current result of this collaboration are the language compiler (not yet distributed), as well as a publication [22].

Beyond the scientific interest of the formal unification of ML programming around a simple and formally defined language, this project may have significant real-life applications in the field of embedded AI, to allow the automatic implementation of advanced AI algorithms (e.g. advanced RL-based motion planning algorithms for autonomous driving). We are exploring this potential through interactions with the ASTRA joint Inria/Valeo team.

8.6 Compositional Analysis of Resource Usage in Software Defined Vehicle

Participants: Julien Deantoni, Robert de Simone.

In a previous project with the *Institut de Recherche Technologique (IRT) Saint-Exupery*, and in connection with local R&D labs of Renault Software Factory and Thales Alenia Space, we considered model-based formal engineering of Interface Description Languages (IDL) to support logical time annotations and abstract temporized functional behavior representations. In this previous work, a very pragmatic simulator was developed. In this simulator, applications are characterized by a temporal profile of their resource usage, the resources are characterized by the number of simultaneous access they support and the result is an evaluation of the time spent waiting for a resource for each application.

This year, we started generalizing previous concepts to estimate, at the system engineering level, the resource usage and potential interferences implied by the deployement of new services in a Software Defined Vehicle. This work is developed in the context of the HAL4SDV European project (see Section 10.3.1).

This activity may eventually merge with the one from Section 8.1 since the goal is to provide compositional analysis means for temporal contracts and their extensions.

8.7 Trustworthy Fleet deployment and management

Participants: Nicolas Ferry, Marie-Agnès Peraldi Frati, Julien Deantoni.

This activity is a follow-up of Nicolas Ferry previous activities in ENACT H2020 project, now renewed since his arrival in Kairos in the DYNABIC HE project (see Section 10.3.2). Continuous and automatic software deployment is still an open question for IoT systems, especially at the Edge and IoT ends. The state-of-the-art Infrastructure as Code (IaC) solutions are established on a clear specification about which part of the software goes to which types of resources. This is based on the assumption that, in the Cloud, one can always obtain the exact computing resources as required. However, this assumption is not valid on the Edge and IoT levels. In production, IoT systems typically contain hundreds or thousands of heterogeneous and distributed devices (also known as a *fleet of IoT/Edge devices*), each of which has a unique context, and whose connectivity and quality are not always guaranteed. In ENACT, we both investigated the challenge of automating the deployment of software on heterogeneous devices and of managing variants of the software which fit different types or contexts of Edge and IoT devices in the fleet. In 2022, GeneSIS (a part of the aforementioned results) was recognized by the EC innovation radar as highly innovant with high maturity level. The natural next step is to investigate how to guarantee the trustworthiness of the deployment when (i) the quality of the devices is not guaranteed, (ii) the context of each device is continuously changing in an unanticipated manner, and (iii) software components are frequently evolving in the whole software stack of each device. In such context, ensuring the proper ordering and synchronization of the deployment actions is critical to improve the quality and trustworthiness and to minimize the downtime.

8.8 Security and Resilience of Cyber Physical Systems

Participants: Nicolas Ferry, Gérald Rocher.

This activity is conducted in the context of the DYNABIC HE project (see Section 10.3.2) in connection with SINTEF and Montimage. The objective of the project is to increase the resilience and business continuity capabilities of European critical services in the face of advanced cyber-physical threats. In this context, we investigated:

1. The landscape and state of the art of existing solutions for: (i) secure orchestration and automated responses in face of cyber attacks [18]; (ii) secure data sharing [14]; (iii) patterns and architectures for IoT security [48].

2. How the behavior of an IoT system can drift at runtime compared to the expected behavior as specified during design. The focus is on delivering multi-concerns (e.g., economics, social, technical) resilience metrics and curves as indica-tors of the effectiveness of resilience solutions [19]

In the next stage, we plan to explore how the behavioral drift analysis solution can be integrated with state-of-the-art security monitoring systems. This integration aims to enhance the understanding and detection of security attacks, as well as their root causes.

8.9 Performance evaluation in ETSI oneM2M standard

Participants: Luigi Liquori, Marie-Agnès Peraldi Frati.

The ETSI Testing Task Force (TTF 019) project is aimed to evaluate a oneM2M-based IoT solution regarding different relevant Key Performance Indicator. Based on the previous work in 2023 [47, 38], we completed in 2024 the project with the following outputs:

- We experimented a profiler tool developed to that aim. The profiler is a standalone software to be run together with a real open-source oneM2M implementation dealing from scripts creating oneM2M "burst" till real case study, as in [34].

- We experimented a simulation tool developed to that aim. The simulation tool is a OMNeT++ library implementing either the deployment model and the case studies, as in [33]; a paper was also published on this issue [17].

- We wrote some deployment guidelines and good practices in order to help open-source communities around oneM2M to get full advantage on our performance evaluation study, as in [31].

8.10 Raising a contact tracing standard to a forecast standard

Participants: Luigi Liquori, Pascal Tempier, Thomas Gorisse, Marie-Agnès Peraldi-Frati, Enrico Scarrone.

In the recent past, we standardized [44] a novel contact tracing protocol, called Asynchronous Contact Tracing (ACT), also using our previous experience on structured overlay networks [39, 41, 46]. ACT traces the presence of Covid19 virus via the IoT connected sensors and makes those informations available anonymously. This year, we extended ACT in order to add a global detection and inter-communication IoT network focused on rapid response to bio-emergencies. This would potentially change the current services already deployed by the National Public Health Institutes to monitor, alert and advise political decision makers, public and military services, environmental institutes and citizens.

This extension could promote an ETSI European standard capable of a real-time “forecasting” of any kind of pathogens and pollutions to people in the EU space, in an anonymous, resilient, and secure way; the standard should be sufficiently flexible and customizable nation-by-nation, according to their peculiar laws.

We also made significant advances in a proof of concepts: sources of the web application (front-end and back-end) and the running android app are fully available on gitlab inria, while the web front-end can be runned by now on act.inria.fr. Those results will continue in 2025 and 2026, in the setting of a new Specialist Task Force (STF 697) funded by ETSI.

8.11 Smart Contract Standards

Participants: Luigi Liquori.

In the context of the ETSI Specialist Task Force (STF655) project, we started in 2024 a standardisation activity on smart contracts, aiming specifically to support the EU Data Act and eIDAS2 proposal directives. This year, the outputs are a scoping study [32] containing the main principle of an original “chain of trust” of electronic signatures to guarantee that every smart contract deployed on a electronic ledger could be legally trusted.

As a student research project, we are currently designing and developing an experimental blockchain allowing dynamic method override in smart contract languages together with the above mentioned chain of trust, following the research line suggested in [37].

In 2025, we will continue this project on using of EU Digital Identity Wallets and electronic signatures for identification with smart contracts and on Policy and security requirements ledgers with smart contracts as a trust service.

8.12 Strong priority and determinacy in timed CCS

Participants: Luigi Liquori, Robert De Simone, Claude Stolze, Michael Mendler.

Building on the classical theory of process algebra with priorities, we identify a new scheduling mechanism, called *sequentially constructive reduction* which is designed to capture the essence of synchronous programming. The distinctive property of this evaluation strategy is to achieve determinism-by-construction for multi-cast concurrent communication. In particular, it permits us to model shared memory multi-threading with reaction to absence as it lies at the core of the programming language Esterel.

In the technical setting of CCS extended by clocks and priorities, we prove for a large class of processes, which we call *structurally coherent*, the Church-Rosser confluence property for constructive reductions. We further show that under some syntactic restrictions, called *pivotable*, the operators of prefix, summation, parallel composition, restriction and hiding preserve structural coherence. This covers a strictly larger class of processes compared to those that are confluent in Milner’s classical theory of CCS without priorities [30].

8.13 A middleware for the experimentation on IoT mobile networks

Participant: Luc Hogie.

Idawi is a middleware for distributed computing on large mobile and heterogeneous dynamic networks [28] developed within the KAIROS and COATI teams since 2021. It aims at providing the Research communities with an experimentation tool for distributed computing in the Edge, the IoT, mobile ad hoc network, etc.

In 2024, we have pursued our work on the use of the concept of a "digital twin" for the decentralized management of large mobile heterogeneous networks, at a middleware-level [29]. In practice, we have implemented in the Idawi middleware a specific (node-local) service hosting and exposing a digital twin of the surrounding network. The nodes within this digital twin (representing the network) are themselves digital twins of their physical counterpart nodes.

This composite digital twin is aimed to be used by other services/applications to 1) discover the routes and resources available into the physical network, as well as to 2) simulate a distributed process. Simulation can be used by any node, on the basis of its local knowledge of the environment (the network). It makes it possible to predict the behavior of complex distributed processes before they are launched across the real system. Simulation results can be then used to drive node's behavior on-the-fly.

9 Bilateral contracts and grants with industry

Participants: Robert de Simone, Frédéric Mallet, Julien Deantoni, Dumitru Potop Butucaru, Luigi Liquori, Marie-Agnès Peraldi Frati, Frédéric Fort.

9.1 Airbus

This collaboration provided us a funding grant for the extension of the Real-Time Systems Compilation method to allow parallelization onto multi-cores with classical ARM or POWER architecture. See Section 8.4 for results in 2024.

9.2 European Standardisation Telecommunication Institute (ETSI)

Task Testing Force 019. This collaboration with ETSI Technical Committee SmartM2M and their members (CNRS, Telecom Italia, Exacta Global Smart Solutions) provided us a support to conduct the performance evaluation, analysis, planning and deployment for some (but not all) oneM2M open source initiatives. A systematic comparative study has been done to compare connectivity, interoperability, data management, security, and complex architecture issues. See Section 8.9 for results in 2024.

Specialist Task Force 655. This collaboration with the ETSI Technical Committee ESI and their members (Universitat Politecnica Catalunya, Infocert, Obserwatorium.biz, SSA ltd, CCC ltd) provided us a support to explore the requirements of Smart Contrats according to the UE Data Act directive, where Smart Contracts should support the exchange of data and their remuneration. Compliance with the new European Digital Identity and Electronic Ledger directive eIDAS2 is also addressed. See Section 8.11 for results in 2024.

Specialist Task Force 697. This new collaboration with the ETSI Technical Committee SmartM2M and their members will provide us a support to extending and a generalizing of the ETSI Asynchronous Contact Tracing Standard (TS 103757), with the aims to develop a breakthrough global detection and Communication Network focused on rapid response to bio-eco-emergencies. See Section 8.10 for results in 2024.

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program

PLoT4IoT

Title: Probabilistic Logical Time for IoT

Duration: 2020 -> 2024

Chinese Coordinator: Min Zhang (zhangmin@sei.ecnu.edu.cn)

French Coordinator: Frédéric Mallet

Partners:

- East China Normal University Shanghai (Chine)

Inria contact: Frédéric Mallet

Summary: The growing importance of Connected Objects in the Internet of Things (IoT) poses new challenges concerning modeling and design of so-called Cyber-Physical Systems (CPS), where cyber/discrete controler programs interplay with physical (often continuous) environments. While there are generally well-established modeling practices in physical science domains (often including discretization), the need for equally formal modeling treatment of reactive control software itself becomes all the more important, since correctness of functional and non-functional properties relies on the whole range of models, including the software executable specification models. The scope of the PLoT4IoT proposal is entirely devoted to the definition and analysis of modeling paradigms relevant for design of (mainly the cyber part of) CPS.

In this context, we shall study extensions to Logical Time models for CPS, dedicated one one hand to uncertainty and variability, on the other hand to spatio-temporal aspects and mobility. These models will be proposed for standardization into the forthcomming version of the OMG UML MARTE profile. On a more abstract level, we shall study the semantics and the analysis methods for open (concurrent) systems featuring explicit handling of data, time, locations, and propose new approaches to formal verification of safety properties of these systems. As a transversal mathematical tool for these works, we plan to develop new efficient stategies for "Satisfiability Modulo Theory" tools adapted to the 3 three modeling theories above.

10.1.2 Participation in other International Programs

Title: Timed-Aware Proof Assistant for ASTD, CCSL and Event-B

Program: MITACS-Inria

Duration: July-November 2024

Canadian Coordinator: Marc Frappier

French Coordinator: Frédéric Mallet

Partner:

- Université de Sherbrooke, Québec (Canada)

Inria contact: Frédéric Mallet

Summary: Algebraic State-Transition Diagrams (ASTD) use process algebraic operators (akin to CSP) to combine state-transition diagrams. In the context of the PhD of Alex Ndouna, we are tring to propose a time extension of ASTD. This extension is based on CCSL. It would allow a holistic approach for dealing with formal requirements that can be functional or non-fonctional. ASTD has a bridge to Event-B that provides a strong support for state-based refinements and theorem prover based on set theory and first-order logics, so widely accessible to a large community. CCSL opens to the path a wide selection of timed and temporal extensions.

Alex Ndouna, who is entering the second year of his PhD (out of 5 years) has received a grant to visit us during five months.

10.2 International research visitors

10.2.1 Visits of international scientists

Andreas Kraft

Status Researcher

Institution of origin: Deutche Telecom

Country: Germany

Dates: June 2024

Context of the visit: extending ACME oneM2M open-source implementation with advance discovery features, as described in [43]

Mobility program/type of mobility: research stay

Besik Dundua

Status Researcher

Institution of origin: Ilia Vekua Institute of Applied Mathematics

Country: Georgia

Dates: August 2024

Context of the visit: foundation of a pattern calculus featuring fuzzy features

Mobility program/type of mobility: research stay

10.2.2 Visits to international teams

Luigi Liquori

Visited institution: University of Bamberg

Country: Germany

Dates: June 2024

Context of the visit: Dynamic and static semantics for deterministic process algebras, at the basis of the programming language Esterel

Mobility program/type of mobility: research stay

10.3 European initiatives

10.3.1 Horizon Europe

HAL4SDV

Participants: Julien Deantoni, Dumitru Potop-Butucaru, Robert de Simone.

HAL4SDV project on cordis.europa.eu

Title: Hardware Abstraction Layer for a European Software Defined Vehicle approach

Duration: From April 1, 2024 to March 31, 2027

Inria contact: Julien Deantoni

Coordinator: Andreas Eckel

Summary: The HAL4SDV proposal aligns with the EU Strategic Research and Innovation Agenda 2022 on Electronic Components and Systems. It aims to pioneer methods, technologies, and processes for series vehicle development beyond 2030, driven by anticipated advancements in microelectronics, communication technology, software engineering, and AI.

HAL4SDV envisions a future where vehicles are fully integrated into smart cities, intelligent highways, and cyberspace, blurring the lines between inside and outside the vehicle. Assumptions include data-centricity, code portability, efficient data fusion, unlimited scalability, real-time capabilities, and robust cybersecurity.

The objectives encompass unifying software interfaces, creating a hardware abstraction framework, enabling Over-The-Air (OTA) updates, designing platform architectures, ensuring hardware abstraction and virtualization, offering hardware support, automating integration, supporting safety features, harnessing edge computing, implementing security measures, and providing essential development tools.

By focusing on these objectives, HAL4SDV aims to establish a unified ecosystem for software-defined vehicles, positioning Europe's automotive industry for continued leadership post-2030 while leveraging existing results and technologies to accelerate progress.

10.3.2 H2020 projects

DYNABIC

Participants: Nicolas Ferry, Gérald Rocher.

We participate to the DYNABIC HE project, jointly with I3S/UniCA Sparks team. DYNABIC stands for: Dynamic business continuity of critical infrastructures on top of adaptive multi-level cybersecurity. The project aims at delivering socio-technical methods, models and tools for resilience management [19]. It will produce and validate a framework that enables system operators to forecast, assess and mitigate in real time business continuity risks and their possible cascading effects. Gérald Rocher is the main contributor to WP4 and 5, whilst Nicolas Ferry is WP7 leader and contributes to WP4 and 5 (Critical infrastructure monitoring and security adaptation).

10.3.3 COST

Participants: Luigi Liquori, Claude Stolze.

We are member of the COST UE network EuroProofNet. EuroProofNet is the European research network on digital proofs aiming at boosting the interoperability and usability of proof systems. It gather more than 500 researchers from 44 different countries. EuroProofNet organizes meetings and schools, and provides grants to its members for short-term scientific missions in another country.

10.3.4 Stardardization initiatives

ETSI TTF 019

Participants: Luigi Liquori, Marie-Agnès Peraldi-Frati.

Title: Performance Evaluation and Analysis for oneM2M Planning and Deployment

Duration: 2022 -> 2024

Inria contact: Luigi Liquori, Marie-Agnès Peraldi-Frati

Summary: oneM2M, the global standard initiative for M2M communications and the IoT, has published several releases. Each release has added new and advanced features for the oneM2M standard in several aspects: connectivity, interoperability, data management, security, complex architecture, etc. At date, many open-source implementation of oneM2M are available. The project will focus on: i) identification of realistic deployments scenarios of oneM2M-based IoT solutions that will serve as baseline scenarios to help IoT platforms vendors to assess the performance of their oneM2M stack including single and multiple vertical domains: ii) specification of a data model for describing deployment scenarios and performance attributes of oneM2M CSE open-source implementations: iii) specification of a simulation model of a oneM2M-based IoT solution: iv) implementation of a software tool to test/evaluate the performances of a oneM2M CSE open-source implementation and to simulate a complete oneM2M-based IoT solution: v) derivation of guidelines and best practices for efficient oneM2M-based IoT solution deployments.

ETSI STF 655

Participants: Luigi Liquori.

Title: Smart Contracts Standards

Duration: 2024 -> 2025

Inria contact: Luigi Liquori

Summary: This proposal is about the development of standards on smart contracts, aiming specifically to support the Data Act proposal, where Smart Contracts can support the exchange of data and their remuneration, based on the concept of Data Spaces. Compliance with the new European Digital Identity and Electronic Ledger frameworks is also addressed. The project consists of the following main activities: i) Developing a scoping study analyzing the requirements on Smart Contracts from the Data Act and eIDAS2 proposals and identifying standardization requirements for smart contracts in data sharing applications; ii) Specify of policy and security requirements for use of electronic ledgers as a trust service in support of smart contracts; iii) Specify the use of EU Digital Identity Wallets and advanced and qualified electronic signatures / seals for identification with smart contracts; iv) Addressing liaisons with initiatives relevant for data spaces in the Digital Europe, Horizon 2020 and Horizon Europe programmes as well as with relevant technical committees at the European and international level will be established as needed. This proposal will also address liaising internationally with ISO/TC 307 and CEN/CENELEC/JTC19 on European block chain standardization requirements.

ETSI STF 697

Participants: Luigi Liquori.

Title: Pandesys

Duration: 2024 -> 2026

Inria contact: Luigi Liquori

Summary: The new project is about an extension and a generalization of the ETSI Asynchronous Contact Tracing Standard (ACT), as defined in the ETSI standard TS 103757 [44]. We aim to develop a breakthrough global detection and Communication Network focused on rapid response to bio-eco-emergencies. The project aims to develop an innovative and standardized IoT oneM2M-based architecture able to: i) collect the information produced by an IoT-based based detection platform, and correlate it to specific location and areas on the territory; ii) elaborate and augment such information, including territory diffusion forecasts, by means of data fusion; iii) empower on a more solid scientific understanding the political decision maker; iv) share the elaborate information with the citizen via Web services; v) enable the citizen to discover their individual exposition to the pathogen in areas visited in the recent past, with a full respect of privacy, according to the GDPR EU regulations.

10.4 National initiatives

ANR Project CAOTIC

Participants: Dumitru Potop-Butucaru, Robert de Simone.

ANR CAOTIC [2022-2026] Collaborative Action on Timing Interferences. Project CAOTIC is an ambitious initiative aimed at pooling and coordinating the efforts of major French research teams working on the timing analysis of multicore real-time systems, with a focus on interference due to shared resources. The objective is to enable the efficient use of multicore in critical systems. Based on a better understanding of timing anomalies and interference, taking into account the specificities of applications (structural properties and execution model), and revisiting the links between timing analysis and synthesis processes (code generation, mapping, scheduling), significant progress is targeted in timing analysis models and techniques for critical systems, as well as in methodologies for their application in industry. D. Potop Butucaru is Inria Principal Investigator (PI).

ANR Project TAPAS

Participants: Frédéric Mallet, Marie-Agnès Peraldi, Julien Deantoni.

The ANR PRC TAPAS (Timed-Aware Proof Assistant System) is a PRC project funded by ANR (AAPG 2024) for 48 months. The national coordinator is I3S (UMR CNRS) and the other partners are LIPN, LMF, IRIT and LACL. The goal is to provide a formal framework to conduct proofs and a formal verification with a continuous refinement from requirements to code. We intend to build on the refinement process of Event-B and extend it to be able to deal with different models of time, logical time, real-time clocks from timed automata and an hybrid model of time coming from tagged signal model. Université de Sherbrooke is an external international partner of this project but is not funded by ANR. Frédéric Mallet is the PI of the project.

ANR-NSF PRCI Project MLOpt

Participants: Sid Touati, Christophe Aliasfrom CASH team (INRIA Lyon) , Ali Jannesari(from University of Iowa, USA) .

Due to the emergence of High-Performance Computing (HPC) systems, there is an increasing demand for codes that leverage the powerful architecture of such systems. One way to achieve high level performance is to parallelize sequentially written programs. Automatic parallelization is a programmer-friendly way to achieve this goal. However, such approaches are often fragile, restricted and lack scalability. Another way to achieve performance is to use fine hand-tuned kernels from high-performances libraries. However finding where to call libraries is highly bug prone and needs to be automatized as well. The goal of the MLOPT project is to investigate how machine learning techniques might enable scalable automatic parallelization with a special focus on high-level task recognition.

Competitivity Clusters

The Kairos team is involved in the actions of the cluster SCS (Systèmes Communicants Sécurisés) and Frédéric Mallet is elected in the steering committee of SCS. One of the most prominent actions is to build, in partnership with Aix-Marseille University, a Digital Innovation Hub, to open the access (with actions of transfer and valorization) to Digital Innovations for companies that would benefit from it, like public institutions (hospitals, human resources, employment institutions) or private companies that could use IoT for agriculture, tourism, smart infrastructures (harbours, buildings, cities).

CNRS GDRs

We are registered members of three GDR funded by CNRS : **SoC^2**, on topics of Hardware/Software codesign and Non-Functional Property modeling for co-simulation; **LTP**, on verification and language design for reactive CPS systems; **GPL**, on software engineering and Domain-Specific Languages.

Grand Défi - Confiance.AI

We participate to the Confiance.AI programme, in the project "Embedded AI". It is the technological pillar of the Grand Défi “Securing, certifying and enhancing the reliability of systems based on artificial intelligence” launched by the Innovation Council. It is the largest technological research programme in the AIforHumanity plan, which is designed to make France one of the leading countries in artificial intelligence (AI). Our technical contributions to this project are described in 7.1.5.

ProgReco Exploratory Action

We started since September 2024 a new Inria Research Exploratory Action called Program Recognition through Machine Learning and Application to Program Optimization. It is a collaboration between Sid Touati from Kairos team and Christophe Alias from Cash team (Inria-Lyon). We are planning to co-advise a master and a PhD student together on the following subject. Program comprehension is a fundamental problem in computer science, with numerous applications (reverse engineering, refactoring, code optimization, etc.) and yet, full automation remains a distant goal. ProgReco aims to explore the specific case of program recognition, that is, the ability to automatically determine the computation performed by a program from a database of standard computations. This is a specialization of program equivalence—which is generally undecidable. The objective is to find the right balance between complexity and recognition power, based on a supervised learning model. In a second phase, we will explore applying program recognition to code optimization by replacing a recognized program with a more efficient version from an optimized library.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

Member of the organizing committees

- Nicolas Ferry was Workshop chair at the IFIP IoT Conference 2024.
- Nicolas Ferry was Member of the organization committee of the 1st International Workshop GRAAL4IoT, co-located with IFIP IoT Conference
- Marie-Agnès Peraldi-Frati was Member of the organization committee of the 1st International Workshop STAND4IoT, co-located with IFIP IoT Conference
- Nicolas Ferry was Member of the organization and steering committee of the 4th International Workshop on MDE for Smart IoT Systems (MESS) co-located with STAF 2024
- Luigi Liquori was General Workshop chair of FSCD 2024.

11.1.2 Scientific events: selection

Member of the conference program committees / Reviews

- Nicolas Ferry was member of the program committees of ANNSIM 2024, STAM'24, and IFIP IoT'24.
- Nicolas Ferry was Workshop chair at the IFIP IoT Conference 2024.
- Marie-Agnès Peraldi-Frati was Workshop chair at the IFIP IoT Conference 2024.
- Frédéric Mallet was a member of program committees and reviewer for international conferences: ABZ 2024, ICECCS 2024, ICFEM 2024, ICTAC 2024, RTCSA 2024, TASE 2024.
- Julien Deantoni was a member of the program committees of MPM4CPS 2024, STAF 2024.

11.1.3 Journal/Conferences

Reviewer - reviewing activities

- Frédéric Mallet has reviewed articles for the following international journals: ACM TOSEM, ACM TECS, ACM TODAES, Elsevier SCP, Elsevier JSA, Springer Nature, Elsevier Software: Practice and Experience.
- Luigi Liquori has reviewed articles for the following international conferences: LICS-24, CSL-24.
- Julien Deantoni has reviewed articles for the following international journals: Springer SOSYM and ACM TECS

Member of the editorial boards

- Julien Deantoni was special guest editor of the ACM TECS special issue on Specification and Design Languages.

11.1.4 Invited talks

- Gérald Rocher, ”Effectiveness Assessment of Cyber-Physical Systems” at Institut de Recherche en Informatique de Toulouse (IRIT), November 2024.
- Frédéric Mallet, "Real-Time extensions for CCSL" at Nanjing University of Aeronautics and Astronautics, Nanjing, China. November 1st 2024.
- Julien Deantoni was a keynote speaker at the SBMF 2024 conference, “Software Language Engineering Towards Formal Systems Engineering: a Journey”.

11.1.5 Leadership within the scientific community

- Luigi Liquori is elected member of FSCD, International Conference on Formal Structures for Computation and Deduction and Elected member of IFIP Working Group 1.6 Rewriting.
- Luigi Liquori is elected member of oneM2M - *oneM2M Sets Standards For The Internet Of Things*, Academia-Relationship Group.
- Luigi Liquori is the Inria point of contact for ECMA, in the group TC 39: *Specifying JavaScript*.
- In the context of the “Engineering of Digital Twin” project call, Julien Deantoni lead the “Model hybridization” internal project.

11.1.6 Scientific expertise

- Frédéric Mallet is the scientific advisor for Université Côte d’Azur on the 3-year MOVE2DIGITAL Digital Europe project of European Digital Innovation Hub. This project includes two main parts. One for test before invest, the other one on academic training. It aims at leveraging the academic expertise of the University on Artificial Intelligence, High-Performance Computing and Cybersecurity to help small and medium entreprises of the region increasing their Competitivity in Europe by performing a digital transformation of their working process.
- Luigi Liquori was reviewer of two COST european propositions.

11.1.7 Standardization committees

- Luigi Liquori and Marie-Agnès Peraldi-Frati are members of oneM2M Consortium - *oneM2M Sets Standards For The Internet Of Things*.
- Luigi Liquori and Marie-Agnès Peraldi-Frati are members of ETSI TC SmartM2M - *Smart Machine-to-Machine Communications, Standards for M2M and the Internet of Things*.
- Luigi Liquori is member of ETSI Technical Committee - *Electronic Signatures and Trust Infrastructures* (ETSI TC ESI).
- Luigi Liquori is member of ETSI Technical Committee (ETSI TC eHEALTH).
- Luigi Liquori is member of AFNOR, *Langages de Programmation* Group.
- Luigi Liquori is member of ISO, JTC1/SC22 *Programming languages, environments and system software interfaces* WG14 and WG22 (C/C++).
- Luigi Liquori is member of ECMA TC 39: *Specifying JavaScript*.

11.1.8 Research administration

- Since January 1st 2022, Frédéric Mallet is the Director of I3S research unit, a joint research unit between CNRS and Université Côte d’Azur, of 270 staff, including 135 permanent staffs.
- Since 2022, Julien Deantoni is a member of the I3S laboratory council.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Master: Dumitru Potop-Butucaru, A synchronous approach to the design of embedded real-time systems, 30h eq TD, EPITA Engineering School, Paris.
- Master: Dumitru Potop-Butucaru, Real-time embedded systems, 42h eq TD, EIDD, École d’Ingenieur Denis Diderot, Université Paris Cité.

- Master: Sid Touati, Architectures de processeurs hautes performances, 30 eq TD, Master 1 informatique, Université Côte d'Azur.
- Master: Sid Touati, Advanced operating systems, 30h eq TD, Master 1 informatique, Université Côte d'Azur.
- Master: Sid Touati, Programmation efficace, 30h eq TD, Master 1 informatique, Université Côte d'Azur.
- Master: Sid Touati, Calculs avancés et performances, 30h eq TD, Master 2 informatique, Université Côte d'Azur.
- Master: Luigi Liquori, Peer-to-peer systems, 32h eq TD, M2, Polytech Nice Sophia, Université Côte d'Azur.
- Master: Julien Deantoni, Domain Specific Languages, 32h eq TD, M2, Polytech Nice Sophia, Université Côte d'Azur.
- Master: Julien Deantoni, Architecting IoT systems, Beyond Functional Correctness, 32h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- Master: Nicolas Ferry, Architecting IoT systems, Beyond Functional Correctness, 8h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- Master: Nicolas Ferry, Web services for the Internet of Things, 4h eq TD, M2 International Ubinet, Université Côte d'Azur.
- Master: Frédéric Mallet, Programmation Synchrone, 32h eq TD, M1, Université Côte d'Azur.
- International Master: Frédéric Mallet, Safety-Critical Systems, 32h eq TD, M1, Université Côte d'Azur.
- International Master: Frédéric Mallet, Software Engineering, 32h eq TD, M1, Université Côte d'Azur.
- License: Luc Hogie, Distributed programming, 28h eq TD, DUT Informatique, Université Côte d'Azur.
- Licence: Sid Touati, Architecture machine, 50 eq TD, L3 informatique, Université Côte d'Azur.
- Licence: Sid Touati, Compilation, 87h eq TD, L3 informatique, Université Côte d'Azur.
- Licence: Sid Touati, Systèmes d'exploitation, 18h eq TD, L2 informatique, Université Côte d'Azur.
- BUT3: Marie-Agnès Peraldi Frati, Virtualisation avancée (30h), Programmation avancée (30h) - IUT Université Côte d'Azur.
- BUT2 : Bases de la Virtualisation, 30h eq TD, SAE, Situations Apprentissages et d'Études 30h eq TD IUT Université Côte d'Azur.
- Licence: Marie-Agnès Peraldi Frati, Introduction à la Programmation 1, 30h eq TD, DS4H portail science, Université Côte d'Azur.
- Licence: Julien Deantoni, Introduction à la Programmation 1, 130h eq TD, DS4H portail science, Université Côte d'Azur.
- BUT1: Nicolas Ferry, Software Quality, 18h eq TD,
- BUT2: Nicolas Ferry, Web Programming, 30h eq TD, IUT Nice Côte d'Azur, Université Côte d'Azur.
- BUT2: Nicolas Ferry, Software Quality, 20h eq TD, IUT Nice Côte d'Azur, Université Côte d'Azur.
- BUT3: Nicolas Ferry, Continuous Delivery, 20h eq TD, Université Côte d'Azur.

- BUT3: Nicolas Ferry, SAE (large semester project), 35h eq TD, Université Côte d'Azur.
- SI5: Nicolas Ferry, Conception Systèmes Cyber-Physiques, 18h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- SI5: Nicolas Ferry, Architecture Beyond Functional Correctness, 8h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- SI5: Gérald Rocher, Conception Logicielle: du Smartphone aux Wearable Computers, 3h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- SI5: Gérald Rocher, Conception Systèmes Cyber-Physiques, 4h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- SI5: Gérald Rocher, Développement Logiciel d'Applications IA embarquées, 34h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- SI5: Gérald Rocher, Développement de Systèmes Cyber-Physiques, 28h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- SI5: Gérald Rocher, Full-Stack Software Engineering for IoT, 8h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- SI5: Gérald Rocher, Architectures à Microservices, 10h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- SI5: Gérald Rocher, Systèmes Intelligents Autonomes, 4h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- PEIP1: Gérald Rocher, Environnements Informatiques, 35h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- BAT3: Claude Stolze, Bâtiment intelligent, 64.5h eq TD, Polytech Nice Sophia, Université Côte d'Azur.
- BAT3: Claude Stolze, Initiation à Programmation VBA, 26.75h eq TD, Polytech Nice Sophia, Université Côte d'Azur.

11.2.2 Supervision

Most of the Kairos members are supervising several tutored students and internships every years.

PhD student supervision:

- Baptiste Allorant is supervised by Frédéric Mallet and Sid Touati
- Joao Cambeiro is supervised by Julien DeAntoni
- Barbara Da Silva Oliveira is supervised by Nicolas Ferry and Julien DeAntoni
- Arseniy Gromovoy is supervised by Robert De Simone
- Maksym Labzhaniia is supervised by Frédéric Mallet and Julien DeAntoni
- Pavlo Tokariev is supervised by Frédéric Mallet and Robert de Simone and he defended in December 2024 [26]
- Enlin Zhu is supervised by Frédéric Mallet

11.2.3 Juries

- Sid Touati was the president of the PhD committee of Hugo Thievenazin in computer science at Ecole Normale Supérieure de Lyon (December 18th, 2024, LIP, Lyon).
- Nicolas Ferry was a referee for the PhD committee of Shivananda Rangappa Poojara on "Design and Orchestration of Scalable, Event-Driven Serverless Data Pipelines for Internet of Things (IoT) Applications" at University of Tartu, Estonia
- Frédéric Mallet was a referee for the PhD committee of Peter Riviere at Toulouse INP / IRIT (June 4th, 2024).
- Frédéric Mallet was a referee for the PhD committee of Diego de Azevedo, at Université de Sherbrooke, Québec, Canada (August 22nd, 2024)
- Frédéric Mallet was a referee for the PhD committee of Morgan Gauthier at ISAE SupAéro, U. Toulouse (October 3rd, 2024).
- Frédéric Mallet was the president of a selection committee for hiring a Professor at Université Côte d'Azur in 2024.
- Julien Deantoni was the president of the PhD committee of Matthias Pasquier at ENSTA Brest (December 19th, 2024, ENSTA, Brest).
- Julien Deantoni was the president of a selection committee for hiring an associate Professor at Université Côte d'Azur in 2024.
- Julien Deantoni was the co-president of a selection committee for hiring an associate Professor at Université Côte d'Azur in 2024.

11.3 Popularization

11.3.1 Terra Numerica

Kairos is involved into Terra Numerica, where it manages the development of many educational software (games portal), and participates to public events. This implies the recruitment and supervision of students at Master-level at DS4H and Polytech Nice. Every semester, we work with 5-6 students.

11.3.2 Others science outreach relevant activities

In 2024, Marie-Agnès Peraldi-Frati participated to the dedicated programme “1 scientifique, 1 classe, Chiche!”, targeted at Junior High School audience, and meant to encourage young people, girls in particular, to consider scientific studies and careers. We animated, jointly with their traditional teacher, a robotic challenge addressed to 13 years old students in a nearby school.

In November 2024, Nicolas Ferry presented a poster at the ETSI Security Conference about DYNABIC: "DYNABIC: Dynamic Business Continuity and Response of Critical Systems against advanced cyber-physical threats".

12 Scientific production

12.1 Major publications

[1] C. André, J. Deantoni, F. Mallet and R. De Simone. ‘The Time Model of Logical Clocks available in the OMG MARTE profile’. In: *Synthesis of Embedded Software: Frameworks and Methodologies for Correctness by Construction.* Ed. by S. K. Shukla and J.-P. Talpin. Chapter 7. Springer Science+Business Media, LLC 2010, July 2010, p. 28. URL: https://hal.inria.fr/inria-00495664 (cit. on p. 3).

[2] Y. Bao, M. Chen, Q. Zhu, T. Wei, F. Mallet and T. Zhou. 'Quantitative Performance Evaluation of Uncertainty-Aware Hybrid AADL Designs Using Statistical Model Checking'. In: *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems* 36.12 (Dec. 2017), pp. 1989–2002. DOI: 10.1109/TCAD.2017.2681076. URL: https://hal.inria.fr/hal-01644285 (cit. on p. 5).

[3] T. Carle, D. Potop-Butucaru, Y. Sorel and D. Lesens. 'From Dataflow Specification to Multiprocessor Partitioned Time-triggered Real-time Implementation *'. In: *Leibniz Transactions on Embedded Systems* (Nov. 2015). DOI: 10.4230/LITES-v002-i002-a001. URL: https://hal.inria.fr/hal-01263994 (cit. on p. 6).

[4] L. Henrio, E. Madelaine and M. Zhang. 'A Theory for the Composition of Concurrent Processes'. In: *36th International Conference on Formal Techniques for Distributed Objects, Components, and Systems (FORTE)*. Ed. by E. Albert and I. Lanese. Vol. LNCS-9688. Formal Techniques for Distributed Objects, Components, and Systems. Heraklion, Greece, 2016, pp. 175–194. DOI: 10.1007/978-3-319-39570-8_12. URL: https://hal.inria.fr/hal-01432917 (cit. on p. 5).

[5] F. Jebali and D. P. Butucaru. 'Ensuring Consistency between Cycle-Accurate and Instruction Set Simulators'. In: *18th International Conference on Application of Concurrency to System Design, ACSD 2018, Bratislava, Slovakia, June 25-29, 2018*. 2018, pp. 105–114. DOI: 10.1109/ACSD.2018.00019. URL: https://doi.ieeecomputersociety.org/10.1109/ACSD.2018.00019 (cit. on p. 6).

[6] L. Liquori and C. Stolze. 'The Delta-calculus: syntax and types'. In: FSCD 2019 - 4th International Conference on Formal Structures for Computation and Deduction. Dortmund, Germany, 2019. DOI: 10.1007/978-3-030-44411-2_6. URL: https://hal.archives-ouvertes.fr/hal-01963662 (cit. on p. 7).

[7] F. Mallet and R. De Simone. 'Correctness issues on MARTE/CCSL constraints'. In: *Science of Computer Programming* 106 (Aug. 2015), pp. 78–92. DOI: 10.1016/j.scico.2015.03.001. URL: https://hal.inria.fr/hal-01257978 (cit. on p. 3).

[8] J.-V. Millo and R. De Simone. 'Periodic scheduling of marked graphs using balanced binary words'. In: *Theoretical Computer Science* 458.2 (Nov. 2012), pp. 113–130. DOI: 10.1016/j.tcs.2012.08.012. URL: https://hal.inria.fr/hal-00764076 (cit. on p. 4).

[9] D. Potop-Butucaru, R. De Simone and J.-P. Talpin. 'Synchronous hypothesis and polychronous languages'. In: *Embedded Systems Design and Verification*. Ed. by R. Zurawski. CRC Press, 2009, pp. 6-1-6–27. DOI: 10.1201/9781439807637.ch6. URL: https://hal.inria.fr/hal-00788473 (cit. on p. 3).

[10] C. Stolze and L. Liquori. 'A Type Checker for a Logical Framework with Union and Intersection Types'. In: FSCD 2020 - 5th International Conference on Formal Structures for Computation and Deduction. Paris, France, 2020. DOI: 10.4230/LIPIcs.FSCD.2020. URL: https://hal.archives-ouvertes.fr/hal-02573605 (cit. on p. 7).

[11] M. E. Vara Larsen, J. Deantoni, B. Combemale and F. Mallet. 'A Model-Driven Based Environment for Automatic Model Coordination'. In: Models 2015 demo and posters. Models 2015 demo and posters. Ottawa, Canada, 1st Oct. 2015. URL: https://inria.hal.science/hal-01198744.

[12] M. Zhang, F. Dai and F. Mallet. 'Periodic scheduling for MARTE/CCSL: Theory and practice'. In: *Science of Computer Programming* 154 (Mar. 2018), pp. 42–60. DOI: 10.1016/j.scico.2017.08.015. URL: https://hal.inria.fr/hal-01670450 (cit. on p. 5).

12.2 Publications of the year

International journals

[13] X. Chen, Z. Jin, M. Zhang, F. Mallet, X. Liu and T. Zhou. 'A Scalable Approach to Detecting Safety Requirements Inconsistencies for Railway Systems'. In: *IEEE Transactions on Intelligent Transportation Systems* 25.8 (Aug. 2024), pp. 8375–8386. DOI: 10.1109/TITS.2024.3418864. URL: https://inria.hal.science/hal-04750626 (cit. on p. 13).

[14] P. Nguyen, A. Goknil, G. Erdogan, S. Tokas, N. Ferry and T. Thao Thi Tran. 'Advances in Secure IoT Data Sharing'. In: *Foundations and Trends® in Privacy and Security*. Foundations and Trends® in Privacy and Security 7.1 (2024), p. 88. DOI: 10.1561/3300000042. URL: https://hal.science/hal-04809549 (cit. on p. 16).

[15] Y. Zhang, F. Mallet, M. Zhang and Z. Liu. 'Specification and Verification of Multi-Clock Systems Using a Temporal Logic with Clock Constraints'. In: *Formal Aspects of Computing* 36.2 (26th June 2024), pp. 1–51. DOI: 10.1145/3670794. URL: https://inria.hal.science/hal-04750634 (cit. on p. 13).

International peer-reviewed conferences

[16] M. Labzhaniia, J. Deantoni, M.-A. Peraldi-Frati and F. Mallet. 'Spatio-Temporal Framework for Verifying Safety Rules in Autonomous Vehicles'. In: MODELS 2024 - 27th International Conference on Model Driven Engineering Languages and Systems. Linz, Austria, 22nd Sept. 2024. DOI: 10.1145/3652620.3687813. URL: https://hal.science/hal-04695647 (cit. on p. 13).

[17] S. Medjiah, T. Monteil, M.-A. Peraldi-Frati and L. Liquori. 'Multi-layered Model for Performance Evaluation of oneM2M-based IoT Solution'. In: *IFIP Advances in Information and Communication Technology*. IFIP-IoT Conference 2024 - 7th IFIP WG 5.5 International Cross-Domain Conference on Internet of Things. Vol. IFIPAICT-737. Internet of Things : 7th IFIP WG 5.5 International Cross-Domain Conference, IFIPIoT 2024, Nice, France, November 6–8, 2024, Proceedings. Nice, France, 6th Nov. 2024. DOI: 10.1007/978-3-031-81900-1_5. URL: https://inria.hal.science/hal-04749511 (cit. on p. 16).

[18] P. Nguyen, R. Dautov, H. Song, A. Rego, E. Iturbe, E. Rios, D. Sagasti, G. Nicolas, V. Valdés, W. Mallouli, A. Cavalli and N. Ferry. 'Towards Smarter Security Orchestration and Automatic Response for CPS and IoT'. In: IEEE CloudCom 2023 - 14th IEEE International Conference on Cloud Computing Technology and Science. Naples (Napoli), Italy, 4th Dec. 2024, pp. 298–302. DOI: 10.1109/CloudCom59040.2023.00055. URL: https://hal.science/hal-04526166 (cit. on p. 16).

[19] G. Rocher, J.-Y. Tigli, S. Lavirotte and N. Ferry. 'A Framework Towards Assessing the Resilience of Urban Transport Systems'. In: *ACM Digital library*. ARES 2024 - Proceedings of the 19th International Conference on Availability, Reliability and Security. ARES '24: Proceedings of the 19th International Conference on Availability, Reliability and Security. Vienna, Austria, 30th July 2024. DOI: 10.1145/3664476.3670435. URL: https://hal.science/hal-04674415 (cit. on pp. 16, 21).

[20] B. da Silva Oliveira, N. Ferry and J. Deantoni. 'Towards Leveraging the Concept of Influence to Enhance Collaborative Cyber-Physical Systems Development'. In: *MODELS*. MPM4CPS 2024 - Multi-Paradigm Modeling for Cyber-Physical Systems @MODELS 2024. Linz, Austria, 22nd Sept. 2024. DOI: 10.1145/3652620.3688568. URL: https://inria.hal.science/hal-04695644 (cit. on p. 14).

[21] P. Tokariev and F. Mallet. 'Real-Time CCSL: Application to the Mechanical Lung Ventilator'. In: *Lecture Notes in Computer Science*. ABZ 2024 – 10th International Conference on Rigorous State Based Methods. Vol. LNCS-14759. Rigorous State-Based Methods: 10th International Conference, ABZ 2024, Bergamo, Italy, June 25–28, 2024, Proceedings. Bergamo, Italy: Springer, 21st June 2024, pp. 289–306. DOI: 10.1007/978-3-031-63790-2_24. URL: https://inria.hal.science/hal-04639949 (cit. on p. 13).

Conferences without proceedings

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