D1.1 MODRIO State-of-the-Art

WP1 Project management

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Authors

Martin Otter	DLR SR, Germany
Peter Fritzson	Linköping University, Sweden
Daniel Bouskela	EDF, France
(with contributions from MODRIO partners)	

Executive summary

This document provides a "State-of-the-Art" overview of the fields in which the ITEA2 research project MODRIO is performed. The goal of MODRIO is to extend modeling and simulation tools based on open standards from system design to system operation. The innovations technically focus on property/requirements modeling, nonlinear state estimation, multi-mode modelling (systems with multiple operating modes and varying number of states), and nonlinear model predictive control.

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1. Overview

The goal of the ITEA2 MODRIO project is to extend state-of-the-art modelling and simulation environments based on open standards to increase energy and transportation systems safety, dependability and performance **throughout their lifecycle**. The focus is on improving the operation of such systems by utilizing nonlinear models for online monitoring, online state estimation, online optimization, and by verifying formally defined requirements.
For most parts of the MODRIO project it is assumed that nonlinear models of the system under consideration are available that are used for the design and evaluation of the system. The major goal of MODRIO is the development of technology and of tool chains to utilize such models directly in online operations of the system, in order to improve the actual performance of the system.
This document provides an overview of the state-of-the-art that is the basis of developments within the MODRIO project. Note, all the Hyperlinks in this document have been checked on April 18, 2016.

2. Modeling and Simulation Software Market

MODRIO is based on "physical modelling and system simulation" where models are mathematically described by nonlinear differential, algebraic and discrete equations. The goal is to use such models for requirement verification and for online operations. To our knowledge, there is currently no general purpose software or modeling standard available for this purpose[1].

Utilizing linear dynamic models in online operations is state-of-the-art since years. Both a rigid mathematical foundation is present, as well as powerful tool chains, such as products from MathWorks, dSPACE, Esterel and others.

MODRIO bases its developments primarily on the following open modeling standards and extends these standards so that online model operations become feasible and practical[2]:

- The Modelica modeling language (Modelica 3.3 rev.1, 2014) to define cyber-physical systems on a high level. Major simulation tool vendors and several SME support Modelica in their CAE tools (for details, see https://www.modelica.org/tools). Modelica is heavily used in industry such as automotive and aerospace companies, power plant providers, and many other companies.
- The Functional Mockup Interface standard (FMI 2.0, 2014) to define dynamic systems on a low level with a mix of XML and C-functions with dedicated interfaces. FMI 1.0 from year 2010 is supported by more than 80 tools (for details, see https://fmi-standard.org/tools).

The only other open modeling standard that could have been used as a basis for MODRIO is the IEEE 1076 standard VHDL-AMS (https://standards.ieee.org/develop/wg/VHDL_AMS.html). However, VHDL-AMS is primarily focused on the electrical domain (and 1-dim. models from other domains), and is not suited to model multi-phase fluid pipe flow or 3-dim. mechanical systems, as needed in the MODRIO project. Furthermore, current VHDL-AMS tools are dedicated to offline simulation and seem to be too far away from providing nonlinear dynamic models in online operations.

There are many proprietary model descriptions and accompanying simulation environments available. However, the MODRIO project shall be based on open modeling standards supported by many tools and therefore these proprietary solutions have not been taken into account.

[1] There are dedicated applications on the market to utilize nonlinear models in online operations, such as the GPS system, the startup optimization BoilerMax of ABB, or software from the game industry.
[2] This requires typically that nonlinear differential-algebraic equations are solved and utilized in online operations.

The following table shows a selection of environments to model and simulate physical systems that are mathematically described by differential equations or differential-algebraic equations. In this table the simulation tool vendors participating in the MODRIO project are not listed (Dassault Systèmes, Modelon, Wolfram MathCore, ITI, LMS, Simpack, EQUA simulation, Linköping University).

Vendor	**Product/Market**
The Mathworks (US)	Matlab/Simulink: General purpose tool for scientific computing. Dominates the market of control-oriented computing. Recent releases include Simscape for physical systems modelling and simulation.
MapleSoft (Canada)	MapleSim: Modelica-based modeling and simulation tool.
AspenTech (US)	Aspen Plus: Conceptual design of chemical processes. Large database of physical properties state functions. Targeted towards the chemical processes industries. Aspen HYSYS: Conceptual design, optimization, business planning, asset management, and performance monitoring for oil & gas production, gas processing, petroleum refining, and air separation industries.
PSE (UK)	gProms: Process modeling technology and model-based engineering for chemical processes industry. gProms aims at process development and design, and optimization of process operations.
Mentor Graphics (US)	Flowmaster V7: Modelling and simulation of thermo-fluid systems. Market includes transportation and energy sectors.
Synopsis (US)	Saber: Multi-domain modelling and simulation software from Synopsis with the main emphasis on electrical and electronic circuits. Supports the VHDL-AMS standard.
ANSYS (US)	Simplorer: Multi-domain modeling and simulation software from ANSYS with the main emphasis on electrical and electronic circuits. Supports the VHDL-AMS standard.
MSC Software (US)	Easy5: Multi-domain modelling and simulation software from MSC (originally developed by Boeing) with many 1D model libraries. The main drawback is that acausal modelling is not supported and therefore there are large restrictions for physical systems modelling.

Except for the specific field of oil-chemical industry, tool vendors do not yet address systems operation, so the Modeling and Simulation (M&S) tools for the most critical aspects of systems operation (e.g. safety) must be developed by the end-users themselves. It is very likely that the systems engineering M&S tool market will be boosted once tools products are extended to systems operation, because (1) the design-operation-design loop for continuous process improvement will then be closed, and (2) return of experience at industries shows that end-users always replace their legacy in-house tools by off-the-shelf tools when can be done without loss of functionalities.

3. MODRIO Goals and State-of-the-Art

In the following sub-sections the state-of-the-art in the various fields of MODRIO are shortly summarized.

3.1. Property/requirement modelling and safety

Property modelling refers to the formal expression of the system's requirements for the purpose of automatic verification of design or operation requirements using **simulation** of a model of the real physical system. The goal in MODRIO is to define requirements formally with a special language or addition of an existing language and check them automatically whenever a system model is **simulated**. It is not intended to perform formal model verification by a model checker (as done by tools such as SMV, NuSMV, SPIN, Prover Plug-In). Model checkers are currently, and for the foreseeable future, not powerful enough to formally verify the complex requirements appearing in industrial systems[3].

As of today, **requirements** in industrial applications are often defined **in natural language in textual form**, either in reports by using for example Microsoft Word, or with dedicated tool support, the latter especially to get support for collaboration, traceability, coverage analysis. There are a huge amount of tools in this area, for example: Rational DOORS from IBM, Reqtify from Dassault Systèmes, OSRMT (GPL2), formalmind Studio (free). The most important (xml-based) exchange format between requirement tools seems to be ReqIF (OMG 2013).

There are also more **formal requirements specification languages** available, such as OCL (Object Constraint Language of OMG, a declarative language for describing rules for UML models), MARTE (Modelling and Analysis of Real-Time and Embedded Systems of OMG), AADL (Architecture Analysis & Design Language of SAE), or PSL (Property Specification Language of IEEE). These languages are focused on discrete-time, software systems and do not address requirements for continuous-time, physics-intensive systems where one must be able to represent physical laws, operational and maintenance procedures, system reconfigurations, uncertainties, sets defined in intention (which are essential to express fault-tolerance requirements).

The goal in MODRIO is to check requirements automatically **by simulation**. There are several tools on the market to define requirements formally and check them by simulation:

Tool	Description
SCADE Design Verifier	Observer blocks have an Alarm Boolean output. The requirements are modeled in the observer with standard SCADE blocks with the goal, that the Alarm output is always false, otherwise the requirement is not fulfilled. SCADE itself allows only simulations of synchronous systems and therefore verification of errors in combination with physical system models is not possible. In the future this may change, because recently SCADE models can be exported as FMI. However, for verification an FMI physical system model has to be co-simulated with the SCADE model configured for verification. This extension seems to be not yet supported by SCADE.
Simulink Verification and Validation and	Toolboxes from Mathworks. The requirements are modeled with assertion blocks with the goal, that the assertion input is always true, otherwise the

[3] For example, a pipe pressure p is computed by the solution of a nonlinear differential algebraic equation system and it is required that $p \geq p_{cavitate}$.

Tool	Description
Design Verifier toolboxes	requirement is not fulfilled. Simulink code can be associated with requirements definitions in IBM DOORS, by providing a link from the Simulink code to the DOORS requirements definition.

The goal in MODRIO is to define requirements formally from the beginning (not via a pure natural language definition) by using a requirements language that is close to the language of a system architect. Furthermore, the (formal) requirements definition must be independent from system models, because they are usually defined before any simulation model is available. It must be easy to connect the requirements definitions to simulation models, when available. There are then also high level operators needed to formulate requirements such as “in every building, at least one pump must be always active”. To our knowledge, there is no software yet on the market with these properties.

Risk assessment and risk management are gaining importance in many industries. More generally, safety and reliability are handled on well-defined processes and using techniques like Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA). These classical analysis techniques which provide a failure frequency and therefore one of the factors for the quantification of risk could ideally be automated, at least to some extent and without loss of effectiveness, if the safety analysis makes use of the information contained in nowadays physical models. The goal in MODRIO is to extract such information from physical models. One of the MODRIO partners has already a product with limited scope in this area: SafetyDesigner an add-on to SimulationX of ITI. This direction shall be further pursued.

3.2. System diagnosis

At the present time, intrusive methods for system diagnosis are still widely used, ranging from visual inspection requiring system shutdown (e.g. steam generators) to invasive and expensive system modifications (e.g. vehicles) to evaluate the desired quantities. Non-intrusive methods for fault diagnosis are studied in the MODRIO project, notably model-based methods. The main difficulty for fault diagnosis is caused by the lack of instruments for tracking critical internal variables of the monitored system. State estimation methods will reduce the need for such instruments.

In power plants, state estimation is performed for monitoring important parameters. The integration of the data reconciliation method is under way into Modelica tools as a result of the ITEA OPENPROD project. However, data reconciliation is limited to the cases where redundant measurements are available and the true state is close to the measured state (a few percents). For more general cases, in particular for predictive simulation, nonlinear Kalman filters and data assimilation related techniques may be used (as data assimilation is already in use for weather prediction for instance).

There is a rigid mathematical foundation, as well as numerical algorithms for advanced, nonlinear state estimation (extended Kalman filters, unscented Kalman filters, moving horizon estimators etc.). However, we are not aware of general purpose software that is available to directly synthesize a nonlinear state estimator from a physical system model. One issue is that state estimator implementation requires a discrete-time formulation, whereas physical system models are continuous-time models and it is non-trivial to transform a continuous-time (hybrid DAE model) to a discrete-time model.

3.3. Operation assistance

The main industrial tools available for operation assistance are the large full-scope training simulators. These simulators cannot be used for online operations, mainly because they are not designed to be used for other purposes than training.

The main issues to be tackled are:

- Keep the models in line with the current operation requirements;
- Keep the models in line with the constant changes in system's behavior due to ageing, system modifications, regulations evolutions…;
- Compute the best estimate of the system's current physical and logical (hybrid) state, for predictive simulation;
- Explore potential dysfunctional situations using models capable of multi-mode switching (cf. following paragraph).

3.4. Systems with multiple operating modes

There is a need to model systems with multiple operating modes. The control system may, for example, use different controllers for normal operation, change of operating point, start-up and shut-down or may even be partly replaced by manual operation. Certain parts of the plant may in some operating modes be turned off. There is also a need to be able to describe failing components (dysfunctional modelling). Models with multiple modes may exhibit varying structure since they may have different levels of description detail, hence different numbers of degrees of freedom or states. At the present time no modelling language (such as Modelica, VHDL-AMS, OpenMAST) and no modelling environment (see table in section 2) is able to describe physical models (so models defined by differential-algebraic equations) with *dynamically varying number of states*. Such systems are called multi-mode systems in MODRIO.

Simulink is able to activate and deactivate input/output blocks and therefore has already some limited capability to simulate systems with dynamically varying number of states.

3.5. Online optimization

Real-time optimizing control systems are becoming popular in the process and power industries. While linear Model Predictive Control (MPC) has long been a standard technology, now non-linear MPC (NMPC) is becoming increasingly used. Application of this class of control algorithms often requires a significant effort, typically using non-standard modelling frameworks, and design and deployment are often based on different codes, each time written from scratch. The use of such advanced control algorithms is often hampered by the lack of adequate tool-chains and standards, and the disproportionally large implementation effort resulting from that. Another difficulty to implement NMPC is its currently low computation efficiency in solving the nonlinear dynamic optimization problem online.

The goal in MODRIO is to utilize a physical model (described in Modelica or FMI) directly in an NMPC environment without manual coding. The MODRIO partner Modelon has already a platform, JModelica.org that allows utilizing physical models described in a subset of Modelica and with required extensions to Modelica for using them in an NMPC environment. We are not aware of other such software on the market.

3.6. Multi-core compilation and model debugging

Applications in the operation phase of a product or installation (e.g. model-based diagnostic systems, and model-predictive control systems) require fast simulation and operation within real-time deadlines. Present modeling, simulation, and online model-based operation technologies and tools seldom exploit the benefits of the multi-core computers and parallel programming. There are some specialized simulator providers (such as CORYS T.E.S.S.) that are able to build full scope simulators based on multi-core hardware. However, the splitting of the simulator between the different cores is done manually and requires a huge amount of work. The goal in MODRIO is to perform the splitting automatically given the overall model, in order to increase the flexibility and reduce the cost of building such large simulators. Thus, model compilation and operation technology that efficiently utilize multi-core platforms are needed. Automatic extraction of functional parallelism from mathematical description works today but only for very small models and with limited generality. More general and scalable mechanisms for automatic extraction of data parallelism and for explicit partitioning of Modelica models for parallel code generation are developed in MODRIO.

Another problem is the difficulty for the typical user to diagnose and locate sources of computation and performance problems/bugs in models used for online operations. Limited user knowledge about the technical details makes the problem worse. Current typical simulation and online operation systems have very little support for such model debugging. Dysfunctional simulation and operation results should be mapped back to the original model structures in order to identify the causes for erroneous behavior.

4. Research Projects in the MODRIO Fields

In the following table the relation of the MODRIO project with respect to other research projects is summarized (if not explicitly marked, the respective research program is from Europe):

Project Name	Cooperative Program	Time period (approx.)	Technical Focus	Relation to, and difference to the MODRIO project
SAFEDOR	FP6	2005 – 2008	Design, operation and regulation for safety.	Risk-Based Design, Operation and Regulation for Safety; especially maritime industry oriented.
SIMPA2	ANR (France)	2006 – 2008	Modelica open source compiler	Foundation of Imagine.Lab AMESim Modelica compiler and current Modelica Scilab compiler.
EUROSYSLIB (summary, web)	ITEA 2	2007 – 2010	Multi-domain Modelica libraries and Modelica infrastructure for system design.	MODRIO utilizes EUROSYSLIB results with the focus on system operation and diagnosis utilizing directly models from system design.
MODELISAR (summary, Wikipedia, FMI standard)	ITEA 2	2008 - 2011	FMI (Functional Mock-up Interface) standard for Model exchange and co-simulation standard with emphasis on automotive industry. The goal is to distribute models on a low level C-code basis. FMI 1.0 released in 2010. In 2016:	MODRIO enhances FMI 1.0 with focus on system operations with multiple modes and utilizes it not only for simulation (as in MODELISAR) but in complex algorithms during online operation (nonlinear state estimation and failure detection, nonlinear model predictive control etc.). FMI 2.0 released July 25, 2014

Project Name	Cooperative Program	Time period (approx.)	Technical Focus	Relation to, and difference to the MODRIO project
			> 80 tools support FMI 1.0	
OPENPROD	ITEA 2	2009 - 2012	Holistic modelling and simulation environment for system design	In MODRIO, tools from this environment are extended for system diagnosis and operation (OpenModelica, JModelica, Wolfram SystemModeler, IDA Simulation)
MODIPRO	System@tic	2010 - 2012	Model-based and learning-based (flight data recorders) diagnosis and prognosis for business aircraft	MODIPRO is focused on discrete event analysis and learning based techniques. There is no use of hybrid models to detect dynamic effects (failures or trends) for diagnosis and prognosis. In particular there is no work on data assimilation.
Embocon	FP7 - STREP	2010 - 2013	Embedded Optimization for Resource Constrained Platforms	The Embocon focus is mainly on the development of numerical high performance optimization algorithms and the deployment on cheap industrial hardware platforms. In MODRIO, the focus is not on the development of numerical algorithms, but how to automatically link design models to numerical algorithms used in online operations.
AVM-META	DARPA (USA)	2010 - 2014	Multi-domain systems engineering, especially vehicles. Verification of requirements, filtering optimal product configuration.	AVM-META has more focus on the design phase including optimal selection of component configurations, also in the presence of stochastics. MODRIO has more focus on online operation. AVM-META uses several modeling formalisms, including Modelica with the tools Dymola and OpenModelica. MODRIO partners LIU and Modelon are involved in the collaboration with AVM-META.
HARMONICS	FP7 Euratom	2011 - 2014	Safety critical software. Formal specification of plant systems requirements, formal modelling of plant systems design (including I&C[4] systems functional requirements specification), formal verification that plant system requirements are	Results regarding property modelling and possibly multi-mode modelling from MODRIO will be used in HARMONICS (HARMONICS already uses results regarding property modelling from the ITEA2 project EUROSYSLIB). The MODRIO partner EDF is involved in this project.

[4] Instrumentation & Control

Project Name	Cooperative Program	Time period (approx.)	Technical Focus	Relation to, and difference to the MODRIO project
			satisfied by design	
Simovate	Vinnova Utmaning (Sweden)	2012 - 2014	Online operator, fast training simulation methods and tools, e.g. for driving industrial vehicles	Simovate has more focus on technology for training simulators. MODRIO is more focused on online operations. MODRIO partners LIU and Modelon also participate in Simovate.
Sys2Soft	Investisse-ments d'Avenir (France)	2012 - 2014	Software technologies for embedded systems involving complex physical components	This project has a strong emphasis on software engineering technologies (open components). One of its sub-projects, however, dealing with physical systems (Modelica models for real-time, safety, stochastic), has an overlap with the corresponding activities in MODRIO. MODRIO partner INRIA also participates in Sys2Soft.
Connexion	Investisse-ments d'Avenir (France)	2012 - 2015	I&C FMEA of nuclear power plants. Use of possibly massive co-simulation (I&C requirements and plant systems behaviour) to verify that plant system requirements are satisfied, to perform FMEA, Probabilistic Safety Assessments, etc.	Results regarding property modelling and possibly multi-mode modelling from MODRIO will be used in Connexion (Connexion already uses results regarding property modelling from the ITEA2 project EUROSYSLIB). The MODRIO partner EDF is involved in this project.
TOICA (Thermal Overall Integrated Conception of Aircraft)	FP7	2013 - 2016	TOICA will demonstrate how to build the complex representation of the thermal behavior of a complete aircraft through a series of “plateaus”.	TOICA is focused on processes and tools for collaborative aircraft design. Therefore, all results from MODRIO are candidates to be used within TOICA, in particular within the Dassault Aviation - Liebherr Aerospace use-case which uses intensively Modelica and FMI. Siemens PLM activities and use -cases will exploit LMS Imagine.Lab AMESim FMI capabilities. MODRIO partners involved in TOICA are Dassault Aviation, Dassault Systèmes, Siemens PLM (formerly LMS Imagine)

5. Literature

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