Proposal to Extend SystemC-AMS with a Bond Graph Based Model of Computation

Torsten Mähne and Alain Vachoux
Laboratoire de Systèmes Microélectroniques (LSM), Ecole Polytechnique Fédérale de Lausanne (EPFL)
EPFL/STI/IMM/LSM, Bâtiment ELD, Station 11, CH-1015 Lausanne, Switzerland
Phone: +41(21)69-36922, E-Mail: torsten.maehne@epfl.ch, WWW: http://lsm.epfl.ch/

Abstract—**There is a need to improve its modelling capabilities of SystemC-AMS concerning conservative continuous time systems involving the interaction of several physical domains and the interaction with digital control components. Bond graphs unify the description of multi-domain systems by modelling the energy flow between the electrical and non-electrical components. They integrate well with block diagrams describing the signal processing part of a system. It is proposed to develop an extension to the current SystemC-AMS prototype, which shall implement the bond graph methodology as a new Model of Computation (MoC).**

SystemC [1] is a C++ library, which allows to model complex digital hardware/software systems, or Systems-on-Chips (SoCs), by mapping them on communicating processes executed and synchronised by a Discrete-Event (DE) MoC based simulation kernel. Advances in processing technologies allow to make SoCs more and more feature rich and heterogeneous by integrating also analogue, RF, and Micro-Electro-Mechanical System (MEMS) components. Several attempts to extend SystemC have been done to support the design of these Analogue and Mixed-Signal (AMS) SoCs. *SystemC-AMS* [2] provides an efficient Synchronous Data Flow (SDF) MoC to model signal processing dominated continuous time behaviours. However, when it comes to modelling conservative systems, SystemC-AMS and SystemC-A [3] use a quite low-level approach with equation setups and analysis methods similar to classic SPICE-like circuits simulators, which causes a simulation performance penalty. *SystemC-WMS* [4] uses another approach from Wave Digital Filter (WDF) theory, where analogue modules communicate by exchanging energy waves. This is implemented using SystemC hierarchical channels, which limits the simulation performance due to the scheduling of discrete events for each time step.

The goal of this work is to improve the modelling and simulation capabilities of SystemC-AMS regarding conservative continuous time components and their interaction with discrete time (digital) control components by implementing a new MoC based on the *bond graph methodology* [5]. This methodology is attractive for the design and verification of AMS-SoCs because it unifies the description of multi-domain systems. Each conservative system can be transformed from its domain specific representation (e.g., electrical circuit, mechanical multi-body system, fluidic networks, thermal networks) to a bond graph representing graphically the energy flow between generalised elements modelling energy sources, resistive/capacitive/inertial behaviour, quantity transformations (also across physical domain boundaries), and energy distribution through junctions. The link to the physical domain is kept through the units attached to the variables and parameters of the generalised elements. This allows for dimensional analysis to discover illegal element interconnexion and equations involving incompatible quantities. One main advantage of bond graphs is that they can be annotated in a systematic way with the *causality*, which visualises the computational structure (Which variables act as inputs and which as outputs?) of the bond graph and allows to sort the element equations in the right order for an efficient model execution. The assigned causalities allow some further formal checks on the model: the number of states and non-states in the system, the presence of algebraic loops during model execution, or if it is an ill-posed model. They also allow for a well integration of bond graphs with signal flow graphs.

The implementation of the bond graph based MoC will profit from the fact that SystemC-AMS is a library on top of the fully-featured C++ language. The integration and synchronisation with the other MoCs, especially the SDF MoC and the DE MoC, is needed. The strong interaction between the analogue and digital parts of a SoC requires to take into account discrete switching of the energy flows inside the bond graphs due to external signals and thus causality changes during the model execution. The research in this field of *hybrid bond graphs*, which incorporate this local switching capability, is still on-going and needs more efforts to find ways to efficiently reassign causality and to regenerate the computational model at runtime when junction switching occurs [6]. Another important aspect is to allow for hierarchical modelling thus implementing aspects of *word bond graphs* [5].

References

[1] *IEEE Standard 1666-2005, SystemC Language Reference Manual*, IEEE, Mar. 2006. [Online]. Available: http://standards.ieee.org/reading/ieee/std/dasc/1666-2005.pdf

[2] A. Vachoux, C. Grimm, and K. Einwich, "Extending SystemC to support mixed discrete-continuous system modeling and simulation," in *Proceedings of the IEEE International Symposium on Circuits and Systems (ISCAS) 2005*, May 23–26 2005, pp. 5166–5169.

[3] H. Al-Junaid, T. Kazmierski, and L. Wang, "SystemC-A modeling of an automotive seating vibration isolation system," in *Forum on Specification and Design Languages (FDL) 2006*. Darmstadt University, Germany: ECSI, Sep. 19–22 2006, pp. 107–112.

[4] S. Orcioni, G. Biagetti, and M. Conti, "SystemC-WMS: A wave mixed-signal simulator," in *Proceedings of the 8th International Forum on Specification & Design Languages (FDL) 2005*. EPFL, Lausanne, Switzerland: ECSI, September 27–30 2005, pp. 61–72.

[5] D. C. Karnopp, D. L. Margolis, and R. C. Rosenberg, *System Dynamics: Modeling and Simulation of Mechatronic Systems*, 4th ed. Wiley, Jan. 2006.

[6] C. D. Beers, E.-J. Manders, G. Biswas, and P. J. Mosterman, "Building efficient simulations from hybrid bond graph models," in *Proceedings of the 2nd IFAC Conference on Analysis and Design of Hybrid Systems*, Alghero, Italy, Jun. 7–9 2006, pp. 71–76. [Online]. Available: http://www.diee.unica.it/~adhs06/CD/PAPERS/WB1.3.pdf

Proposal to Extend SystemC-AMS with a Bond Graph Based Model of Computation

Torsten Mähne   Alain Vachoux

Laboratoire de Systèmes Microélectroniques (LSM)
École Polytechnique Fédérale de Lausanne (EPFL)
Lausanne, Switzerland

C/C++-Based Modelling of Embedded Mixed-Signal Systems Workshop
25 to 26 June 2007 in Dresden

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Contents

System-on-a-Chip (SoC) Design Process Issues

Issues to be addressed in the SoC design:

- Increasing complexity (computing and communication capabilities),
- Significant heterogeneity (analogue/RF/digital hardware, embedded software, sensors, and actuators),
- Increasing environmental awareness (energy saving, battery operated system, environmental monitoring and interaction),
- Increasing sensitivity to Si technologies (deep sub-micron processes),
- Increasing re-use of subsystems (ever shrinking time to market).

Requiring: Early partition decisions $\longleftrightarrow$ easy reuse and retargeting

$\leadsto$ Modelling with domain specific abstraction concepts – also called Models of Computation (MoCs)

$\leadsto$ C-based design methodologies with strong links to HDL-based design methodologies as implementation path

System-on-a-Chip (SoC) Design Process Issues

Issues to be addressed in the SoC design:

- Increasing complexity (computing and communication capabilities),
- Significant heterogeneity (analogue/RF/digital hardware, embedded software, sensors, and actuators),
- Increasing environmental awareness (energy saving, battery operated system, environmental monitoring and interaction),
- Increasing sensitivity to Si technologies (deep sub-micron processes),
- Increasing re-use of subsystems (ever shrinking time to market).

Requiring: Early partition decisions $\longleftrightarrow$ easy reuse and retargeting

$\leadsto$ Modelling with domain specific abstraction concepts – also called Models of Computation (MoCs)

$\leadsto$ C-based design methodologies with strong links to HDL-based design methodologies as implementation path

State of the Art of AMS-Extensions to SystemC

SystemC-AMS [Fraunhofer IIS/EAS, Dresden, Germany]:

- Synchronous Data Flow (SDF) MoC for block diagrams
- Conservative linear electrical network MoC (Mini-SPICE)
- Synchronisation layer between AMS Extension and SystemC kernel

SystemC-A [University of Southampton, UK]:

- Analogue modules described trough user-defined ODEs and DAEs
- Modified Nodal Analysis (MNA) of networks of analogue modules
- Implementation modifies the SystemC kernel

SystemC-WMS [Università Politecnica della Marche, Ancona, Italy]:

- Analogue module response described using WDF a, b parameters
- Modules exchange energy waves through connectivity defining channels
- Dynamic scheduling of discrete events for each analogue solution point

Missing: Formalism for high-level description and efficient simulation of the conservative multi-domain components of AMS-SoCs.

State of the Art of AMS-Extensions to SystemC

SystemC-AMS [Fraunhofer IIS/EAS, Dresden, Germany]:

- Synchronous Data Flow (SDF) MoC for block diagrams
- Conservative linear electrical network MoC (Mini-SPICE)
- Synchronisation layer between AMS Extension and SystemC kernel

SystemC-A [University of Southampton, UK]:

- Analogue modules described trough user-defined ODEs and DAEs
- Modified Nodal Analysis (MNA) of networks of analogue modules
- Implementation modifies the SystemC kernel

SystemC-WMS [Università Politecnica della Marche, Ancona, Italy]:

- Analogue module response described using WDF a, b parameters
- Modules exchange energy waves through connectivity defining channels
- Dynamic scheduling of discrete events for each analogue solution point

Missing: Formalism for high-level description and efficient simulation of the conservative multi-domain components of AMS-SoCs.

State of the Art of AMS-Extensions to SystemC

SystemC-AMS [Fraunhofer IIS/EAS, Dresden, Germany]:

- Synchronous Data Flow (SDF) MoC for block diagrams
- Conservative linear electrical network MoC (Mini-SPICE)
- Synchronisation layer between AMS Extension and SystemC kernel

SystemC-A [University of Southampton, UK]:

- Analogue modules described trough user-defined ODEs and DAEs
- Modified Nodal Analysis (MNA) of networks of analogue modules
- Implementation modifies the SystemC kernel

SystemC-WMS [Università Politecnica della Marche, Ancona, Italy]:

- Analogue module response described using WDF a, b parameters
- Modules exchange energy waves through connectivity defining channels
- Dynamic scheduling of discrete events for each analogue solution point

Missing: Formalism for high-level description and efficient simulation of the conservative multi-domain components of AMS-SoCs.

State of the Art of AMS-Extensions to SystemC

SystemC-AMS [Fraunhofer IIS/EAS, Dresden, Germany]:

- Synchronous Data Flow (SDF) MoC for block diagrams
- Conservative linear electrical network MoC (Mini-SPICE)
- Synchronisation layer between AMS Extension and SystemC kernel

SystemC-A [University of Southampton, UK]:

- Analogue modules described trough user-defined ODEs and DAEs
- Modified Nodal Analysis (MNA) of networks of analogue modules
- Implementation modifies the SystemC kernel

SystemC-WMS [Università Politecnica della Marche, Ancona, Italy]:

- Analogue module response described using WDF a, b parameters
- Modules exchange energy waves through connectivity defining channels
- Dynamic scheduling of discrete events for each analogue solution point

Missing: Formalism for high-level description and efficient simulation of the conservative multi-domain components of AMS-SoCs.

Overview on the Bond Graph Methodology (Paynter, 1959)

- Methodology, which unifies the description of multi-domain systems
- Every conservative system model can be transformed from its domain-specific representation (e.g., electrical circuit, mechanical multi-body system, fluidic networks, thermal networks) to a bond graph
- Bond Graphs represent graphically the energy flow between the electrical and non-electrical components of a system
- Bond graphs integrate well with block diagrams describing the signal processing part of a system
- Used in mechanical engineering, mechatronics, and control theory
- Available are bond graph tools (MTT, 20-sim, Enport, . . .) and toolboxes for Matlab/Simulink, Mathematica, Modelica, . . .
- But hardly used in microelectronics community due to missing EDA tool links

Basic Definitions

$$El_1 \xrightarrow[f]{e} El_2$$

- Bond: energy exchange link between ports of subsystems El_1 and El_2
- Power variables: effort e and flow f associated with the bond
- Power: $P(t) = e(t) \cdot f(t)$
- Energy flow direction: indicated by half-arrow for $e \geq 0$ and $f \geq 0$
- Energy variables: needed for the description of dynamic systems
  - (generalised) momentum: $p(t) = \int^t e(t)\, dt$
  - (generalised) displacement: $q(t) = \int^t f(t)\, dt$
- Energy: $E(t) = \int^t P(t)\, dt$, $E(q) = \int^q e(q)\, dq$, $E(p) = \int^p f(p)\, dp$

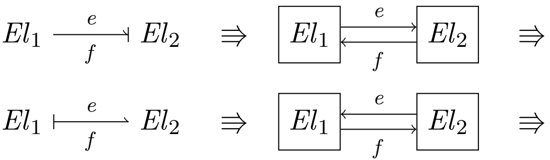
Power and Energy Variables for Different Physical Domains

Physical domain	Effort $e(t)$	Flow $f(t)$	(Generalised) momentum $p(t)$	(Generalised) displacement $q(t)$
electrical	voltage, $[v] = \text{V}$	current, $[i] = \text{A}$	flux linkage variable, $[\lambda] = \text{V}\cdot\text{s}$	charge, $[q] = \text{A}\cdot\text{s}$
mechanical translational	force, $[F] = \text{N}$	velocity, $[v] = \text{m}/\text{s}$	momentum, $[p] = \text{N}\cdot\text{s}$	displacement, $[x] = \text{m}$
mechanical rotational	torque, $[\tau] = \text{N}\cdot\text{m}$	angular velocity, $[\omega] = \text{rad}/\text{s}$	angular momentum, $[p_\tau] = \text{N}\cdot\text{m}\cdot\text{s}$	angle, $[\theta] = \text{rad}$
hydraulic	pressure, $[p] = \text{Pa}$	volume flow rate, $[Q] = \text{m}^3/\text{s}$	pressure momentum, $[p_p] = \text{N}\cdot\text{s}/\text{m}^2$	volume, $[V] = \text{m}^3$

Interpretation of a Bond as a Bilateral Signal Flow

- The energy exchange causes the effort and flow variables to act in opposite directions.

⇝ Determines the computational direction, which is indicated by the causal stroke (perpendicular stroke at one end, where e acts as input):



$$El_2.e := El_1.e \qquad El_1.f := El_2.f$$

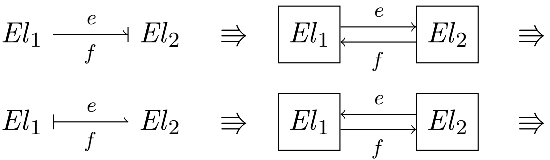
$$El_1.e := El_2.e \qquad El_2.f := El_1.f$$

- The equations describing the element behaviour impose a required, preferred, or free causality (effort-in or effort-out) on the element ports.
- Causalities assigned to one port need to be propagated as constraints to all related ports.
- Methods like the Sequential Causality Assignment Procedure (SCAP) exist to complete systematically the causality of a bond graph.

Interpretation of a Bond as a Bilateral Signal Flow

- The energy exchange causes the effort and flow variables to act in opposite directions.

⤳ Determines the computational direction, which is indicated by the causal stroke (perpendicular stroke at one end, where e acts as input):

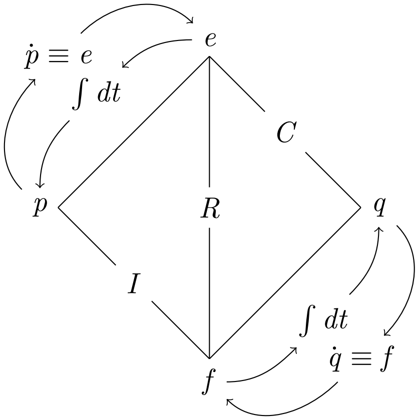


$$El_2.e := El_1.e \qquad El_1.f := El_2.f$$

$$El_1.e := El_2.e \qquad El_2.f := El_1.f$$

- The equations describing the element behaviour impose a required, preferred, or free causality (effort-in or effort-out) on the element ports.
- Causalities assigned to one port need to be propagated as constraints to all related ports.
- Methods like the Sequential Causality Assignment Procedure (SCAP) exist to complete systematically the causality of a bond graph.

Tetrahedron of State



1-Port Bond Graph Elements

Name	Symbol	General relation	Linear relation	Examples
(Generalised) resistor	$\overset{e}{\underset{f}{\longmapsto}} R$ $\overset{e}{\underset{f}{\longrightarrow\!\!\mid}} R$	$e = \Phi_R(f)$ $f = \Phi_R^{-1}(e)$	$e = Rf$ $f = \frac{1}{R} e$	electrical resistor, translational damper, hydraulic throttle
(Generalised) capacitor	$\overset{e}{\underset{f = \dot{q}}{\longrightarrow\!\!\mid}} C$ $\overset{e}{\underset{f = \dot{q}}{\longmapsto}} C$	$q = \Phi_C(e)$ $e = \Phi_C^{-1}(q)$	$q = Ce$ $e = \frac{1}{C} q$	electrical capacitor, spring, gravity tank, accumulator
(Generalised) inductor	$\overset{e = \dot{p}}{\underset{f}{\longmapsto}} I$ $\overset{e = \dot{p}}{\underset{f}{\longrightarrow\!\!\mid}} I$	$p = \Phi_I(f)$ $f = \Phi_I^{-1}(p)$	$p = If$ $f = \frac{1}{I} p$	electric inductor, mass, section of a fluid-filled pipe with fluid inertia

- Generalisations to multi-port R, I, C field elements facilitate the modelling of distributed elements and transducers

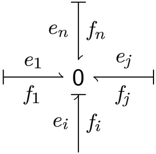
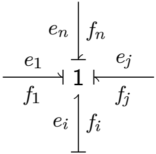
1-Port Bond Graph Elements (Continued)

Name	Symbol	General relation	Examples
Effort source	$S_e \xrightarrow[f]{e}\vert$	$e(t)$ given, $f(t)$ arbitrary	voltage, force, pressure sources
Modulated effort source	$\xrightarrow{e(t)} S_e \xrightarrow[f]{e}\vert$	$e(t)$ given through signal, $f(t)$ arbitrary	
Flow source	$S_f \vert\!\xrightarrow[f]{e}$	$f(t)$ given, $e(t)$ arbitrary	current, velocity, volume flow rate sources
Modulated flow source	$\xrightarrow{f(t)} S_f \vert\!\xrightarrow[f]{e}$	$f(t)$ given through signal, $e(t)$ arbitrary	

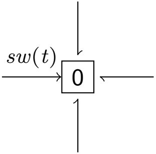
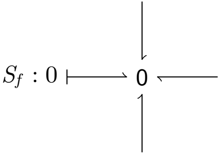
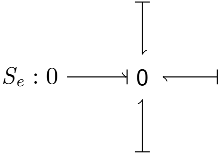
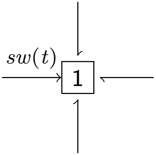
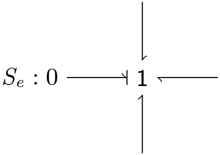
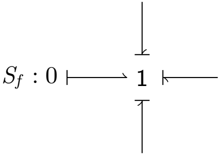
2-Port Bond Graph Elements

Name	Symbol	General relation	Examples
(Generalised) transformer	$\vdash\!\xrightarrow[f_1]{e_1} TF \vdash\!\xrightarrow[f_2]{e_2}$ $\xrightarrow[f_1]{e_1}\!\dashv TF \xrightarrow[f_2]{e_2}\!\dashv$	$e_1 = me_2,\ f_2 = mf_1$ $e_2 = \frac{1}{m}e_1,\ f_1 = \frac{1}{m}f_2$	electrical transformer, ideal rigid lever, hydraulic ram
Modulated (generalised) transformer	$\xrightarrow[f_1]{e_1} \overset{r(t)\downarrow}{MTF} \xrightarrow[f_2]{e_2}$	$e_1 = m(t)e_2,\ f_2 = m(t)f_1$	autotransformer with wiper, geometric transformations
(Generalised) gyrator	$\vdash\!\xrightarrow[f_1]{e_1} GY \xrightarrow[f_2]{e_2}\!\dashv$ $\xrightarrow[f_1]{e_1}\!\dashv GY \vdash\!\xrightarrow[f_2]{e_2}$	$e_1 = rf_2,\ e_2 = rf_1$ $f_2 = \frac{1}{r}e_1,\ f_1 = \frac{1}{r}e_2$	electrical gyrator, gyroscope, voice coil transducer
Modulated (generalised) gyrator	$\xrightarrow[f_1]{e_1} \overset{r(t)\downarrow}{MGY} \xrightarrow[f_2]{e_2}$	$e_1 = r(t)f_2,\ e_2 = r(t)f_1$	gyroscope with variable rotor speed, voice coil with variable transduction coefficient

n-Port Bond Graph Elements

Name	Symbol	General relation	Examples
flow junction, 0-junction, common effort junction		$e_1 = \ldots = e_i = \ldots = e_n$ $f_i = -\left(\sum_{j=1, j\neq i}^{n} f_j\right)$	parallel connexion of electrical conductors; situation involving a single force and n velocities summing up to zero; parallel connexion of hydraulic passages
effort junction, 1-junction, common flow junction		$f_1 = \ldots = f_i = \ldots = f_n$ $e_i = -\left(\sum_{j=1, j\neq i}^{n} e_j\right)$	series connexion of electrical conductors; dynamic equilibrium of n forces associated with a single velocity; series connexion of hydraulic passages

Hybrid Bond Graphs: Switching with Controlled Junctions

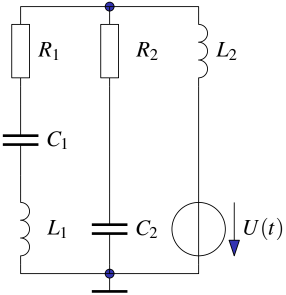
Name	Symbol	On-state	Off-state
Controlled 0-junction			
Controlled 1-junction			

- Extension allowing for discrete switching of energy flows
- Switching of the controlled junctions requires causality reassignment

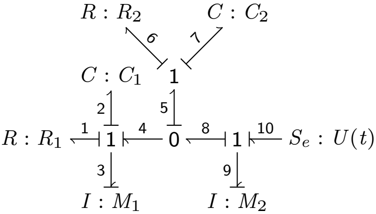
⇝ Simulation performance penalty due to required solver reinitialisation

Transformation of an Electrical Circuit to a Bond Graph

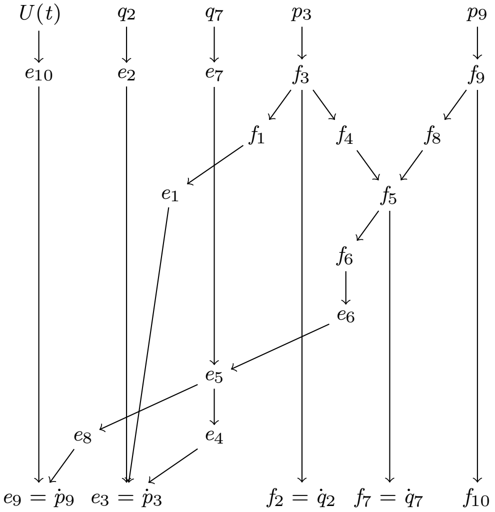
Electrical circuit:



Equivalent causal bond graph:

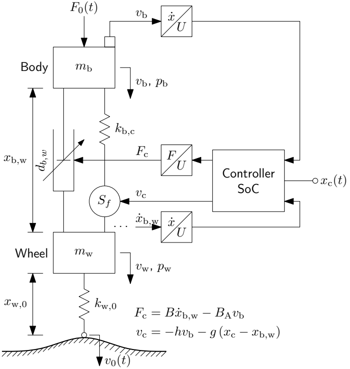


Computational structure:

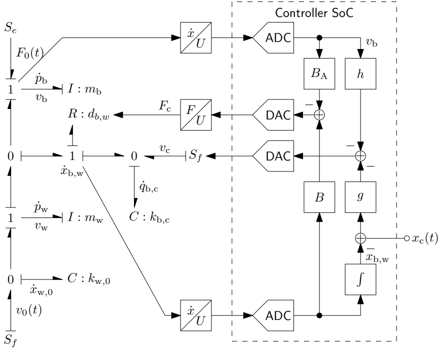


Modelling a Multi-Domain AMS System

Example: Car wheel model of an electronically controlled suspension system incorporating a semi-active damper and a fast load-leveller [Karnopp, 2006]

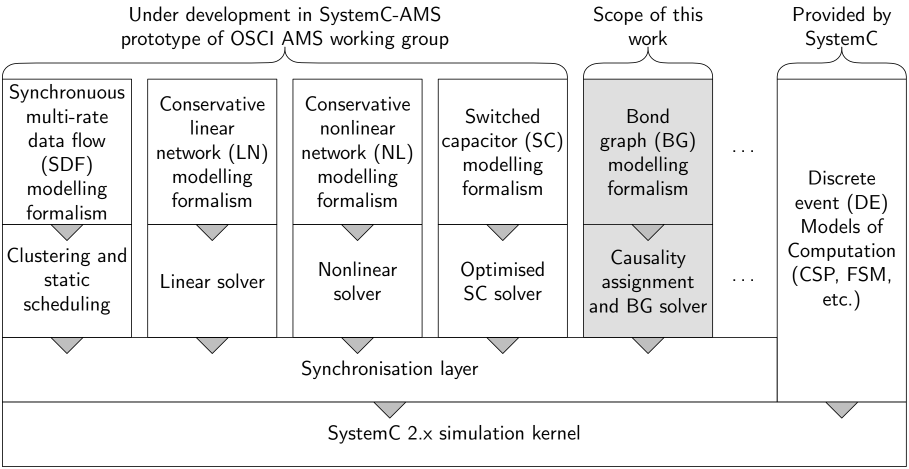


"Classic" domain-specific system representation



Equivalent representation using bond graphs for the energy conservation part and block diagrams for the signal processing part

Architecture of SystemC-AMS



Advantages from the SystemC-AMS Bond Graph Extension

- Description of conservative multi-domain systems:
  - in a unified way independent of the particular physical domain
  - on a higher abstraction level than generalised networks
  - in a modular way allowing to add/remove 2^{nd}-order behaviour
- Good integration with block diagrams (SDF MoC) and discrete event models (switching energy flows)
- Visualise at the same time the energy flow through the system and the computational structure
- Higher simulation performance compared to generalised network solvers due to equation reordering allowing for procedural model execution
- Causality analysis allows for further formal checks:
  - number of states and non-states in the system
  - presence of algebraic loops during model execution
  - detection of ill-posed models
  - ⇝ giving insight into the model's physical and computational structure

Requirements to the SystemC-AMS Bond Graph Extension

High simulation performance: avoid global DAE system setup $\rightsquigarrow$ reorder the equation for fast procedural execution

Hierarchical modelling: using word bond graphs and equation reordering across the module boundaries

Integration with the other MoCs: especially SDF MoC for block diagrams and DE MoC for digital control and switching

Semiformal checks to audit the model: number of states and non-states, presence of algebraic loops, ill-posed model, usage of incompatible units of measurement

Clear specification of the physical domain: annotate power/energy variables and element parameters with their measurement units $\rightsquigarrow$ dimensional analysis

Implementation Path for the Bond Graph Extension

High simulation performance: implement the bond graph elements as classes, assign causalities to a bond graph using SCAP, and execute the instantiated elements in the determined order

Hierarchical modelling: implement bond ports, flatten the module hierarchy to group all connected bond graph elements into a cluster

Integration with the other MoCs: execute the bond graph clusters inside the loop of the associated SDF cluster, reassign causalities when switching occurs at a junction due to a discrete event

Semiformal checks to audit the model: to be done at elaboration time after the causality analysis

Clear specification of the physical domain: make use of the Boost quantitative units library $\rightsquigarrow$ compile time dimensional analysis

Conclusions and Outlook

- Conservative systems modelling with SystemC-A(MS) quite low-level: equation setup, analysis method, and performance similar to SPICE
- Bond graph methodology offers advantages for the design and verification of AMS-SoCs
- It unifies the description of electrical and non-electrical components on various levels of abstraction
- Causality analysis of bond graphs allow to optimise the model execution and gives insight into the physical and computational structure of the system
- Requirements and planned implementation path for the SystemC-AMS Bond Graph Extension were sketched out

$\leadsto$ Input for the specification and design of the extension

References

Al-Junaid, H., T. Kazmierski, and L. Wang: *SystemC-A modeling of an automotive seating vibration isolation system.*
In *Forum on Specification and Design Languages (FDL) 2006*, pp. 107–112, Darmstadt University, Germany, Sept. 19–22 2006. ECSI, ISBN 978-3-00-019710-9.

Beers, C.D., E.J. Manders, G. Biswas, and P.J. Mosterman: *Building efficient simulations from hybrid bond graph models.*
In *Proceedings of the 2nd IFAC Conference on Analysis and Design of Hybrid Systems*, pp. 71–76, Alghero, Italy, June 7–9 2006.
http://www.diee.unica.it/~adhs06/CD/PAPERS/WB1.3.pdf, visited on 2006-09-28.

Biagetti, G. and S. Orcioni: *SystemC-WMS: Analog Modeling in SystemC.*
Università Politecnica della Marche, Ancona (AN), Italy, 2004–2006.
http://www.deit.univpm.it/systemc-wms/, visited on 2007-06-04.

HighTech Consultants: *Home of Bond Graphs—The System Modelling World*, 2005.
http://www.bondgraph.info/, visited on 2007-04-18.

Karnopp, D.C., D.L. Margolis, and R.C. Rosenberg: *System Dynamics: Modeling and Simulation of Mechatronic Systems.*
Wiley, 4th ed., Jan. 2006.

SystemC-AMS Study Group: *Homepage of the SystemC-AMS Study Group*, 2006.
http://www.systemc-ams.org/, visited on 2006-03-10.