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Virtual prototyping of pressure driven microfluidic systems with SystemC-AMS extensions

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ABSTRACT

The design of "Lab on a Chip" microfluidic devices is, typically, preceded by a long and costly period of prototyping stages in which the system is gradually refined by an iterative process, involving the manufacturing of a physical prototype and the making of a lot of laboratory experiments. In this scenario, a virtual prototyping framework which allows the emulation of the behavior of the complete system is greatly welcome. This paper presents such a framework and details a virtual prototyping methodology able to soundly handle microfluidic behavior based on SystemC-AMS extensions. The use of these extensions will permit the communication of the developed microfluidic models with external digital or mixed signal devices. This allows the emulation of the whole Lab on a Chip system as it usually includes a digital control and a mixed-signal reading environment. Moreover, as SystemC-AMS is also being extended to cover other physical domains within the CATRENE CA701 project, interactions with these domains will be possible, for example, with electromechanical or optical parts, should they be part of the system. The presented extensions that can manage the modeling of a micro-fluidic system are detailed. Two approaches have been selected: to model the fluid analytically based on the Poiseuille flow theory and to model the fluid numerically following the SPH (Smoothed Particle Hydrodynamics) approach. Both modeling techniques are, by now, encapsulated under the TDF (Timed Data Flow) MoC (Model of Computation) of SystemC-AMS.

1. Introduction

Cyber-physical systems usually encompass several physical domains in mutual interaction. The precise simulation of involved domains, by specific tools, is feasible (and sometimes done) but this is not usually profitable because it is usually very time consuming and the joint behavior of the system is not predicted. Moreover, it leads to a long iterative process which is, sometimes, replaced by a hardware prototyping process with real devices.

The opportunity for a unified simulation of different physical domains can be, up to date, partially addressed with existing research and commercial tools. On the research and open-source side, Ptolemy [1] and Modelica [2] have to be highlighted. The first one can have a wide variety of MoCs and, the second one, proposes a wide library of components (described with a specific object-oriented open language and supported by several free and commercial tools) in several physical domains. The presented approach works at a lower abstraction level than Ptolemy, enabling to give more physical details. Compared with Modelica, the presented approach allows an easier communication with digital control (and its embedded software) due to the integration into a SystemC environment.

On the commercial side, several tools are available and they usually rely on numerical methods like FEM (Finite Elements). Good examples of this kind of tools are COMSOL [3], ANSYS [4] or 3DS [5]. The use of these tools to describe a device implies long periods of time. Furthermore, they are highly computationally complex. They can be used for very detailed simulations of concrete locations but they are not suitable for fast prototyping of

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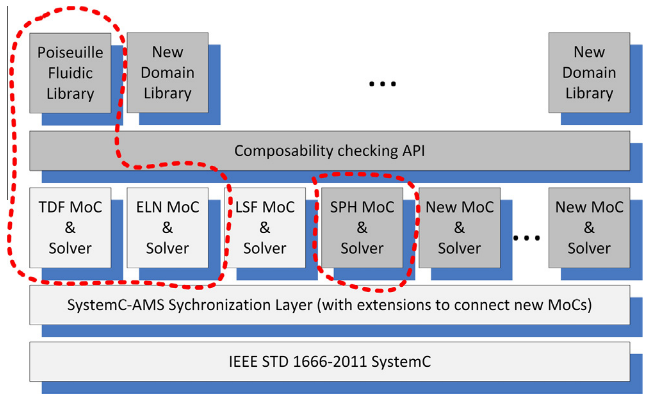

Fig. 1. SystemC-AMS extensions (dark grey). Locations of presented approaches (dashed line).

complete systems. On the other hand, they do not include the embedded software interaction. Other relevant tools on the commercial side are Matlab/Simulink/Simscape [6], LMS Imagine.Lab Amesim [7] and those based on previously mentioned Modelica language (Dymola [8], SimulationX [9], etc.). Again, the advantage of the proposed approach is the use of a standard language that will ease the seamless integration with digital, mix-signal and, in general, with other physical domains.

The advance in micro-nano-electronics fabrication allows the integration of multi-physical systems in single chips which are, in turn, highly integrated with microelectronic embedded systems. In this scenario, the goal of the CATRENE CA701 H-INCEPTION project [10] is to develop a design environment for multi-domain microelectronics assisted systems where the system definition, its design partitioning across the different physical domains, and its integral functionality can be analyzed and verified including the interaction with the overall application environment. On the modeling side, the language proposed is SystemC-MDVP where MDVP stands for Multi-Domain Virtual Prototypes.

SystemC-MDVP is itself an extension of SystemC-AMS [11] which is already an extension of SystemC [12]. The modeling of HW/SW parts as well as the AMS sections is well covered by well-known capabilities of SystemC-AMS. Other physical domains have to be supported by defining and integrating the necessary MoCs.

One of the proof-of-concept multi-domain applications that will be modeled in the project is a prototype of a point-of-care blood analysis system which includes a microfluidic sub-system. The analysis procedure is controlled by a microcontroller which activates pistons and valves in order to move and mix the blood samples with several reagents that imply several biochemical processes. The final biochemical reaction is electrically monitored with an AMS device, digitally converted and sent back for characterization.

Micro and nano-fluidic devices are being widely used for several application areas: Clinical diagnostics, advanced sequencing, drug discovery, environmental monitoring and much more. There are several kind of devices considering the way they move and process the fluids but two main groups can be distinguished: flow based, with several mechanisms to manage the fluidic flows, and discrete droplet (also known as digital) based [13,14]. The microfluidic systems considered in the presented approach are pressure-driven flow-based.

Two modeling approaches have been followed for the emulation with SystemC-AMS extensions of pressure-driven microfluidic devices. The first one involves the analytical solution based on well-known Poiseuille flows [15,16]. This is explained with more detail in the Section 2 of this paper. The second modeling scheme is based on the numerical and geometric solution called Smoothed Particle Hydrodynamics (SPH) [17,18]. This second approach is detailed in Section 3 of this paper.

Both Poiseuille and SPH modeling approaches have in common the property of being simpler (and consequently faster) in the definition of the model and in the execution itself, than other more accurate numerical methods (FEM, for instance). The final goal is to be able to have an environment, based on SystemC-MDVP, for simulation of all the involved physical domains at a high-level of abstraction, which gives the user a rapid idea of the behavior of the whole system in order to reduce the number of prototyping stages. Furthermore, by simulation, some features can be checked that can be unaffordable by real prototyping, allowing the implementation of better products.

In Fig. 1, the SystemC-AMS extension approach, which is being developed and extended in the project, is depicted. The dark grey boxes represent areas of extension and the light grey boxes represent standard areas. For the modeling of new physical domains, it is sometimes necessary to add a new specific Model of Computation (MoC) and Solver. This was the case for the SPH approach because the current SytemC-AMS implementation does

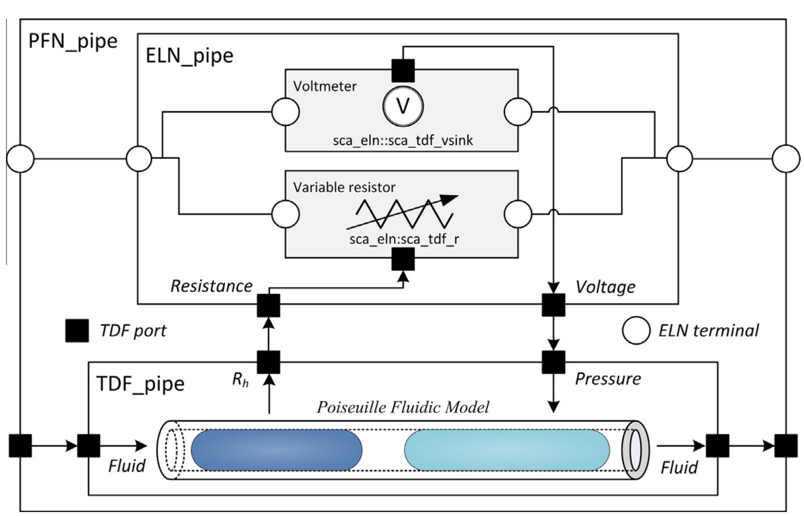

Fig. 2. Two SystemC-AMS components to describe one fluidic pipe.