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System-Level Simulation Using Mixed-Nature Models

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Miniaturized, integrated sensors and actuators are more and more used in microsystem applications. In order to promote their use further, specialists must make them more accessible to system designers. This can be done through behavioral modeling of sensors and actuators. The resulting models can be used in conjunction with models of the associated electronics to simulate a complete microsystem. Additionally, models of the non-electrical environment (stimuli, other devices) should be developed too. This paper presents our contribution to solve this modeling and simulation problem. We propose to use and eventually extend existing analog and mixed electronic design tools in such a way that microsystems can be simulated globally at an early stage of the design.

I. INTRODUCTION

In this paper, we focus on modern microtechnology systems, also called microsystems. They can be defined as systems of small dimensions essentially composed of an information-capturing part (a sensor), a signal processing part, and a part which performs some action (an actuator). Often, the sensors and actuators are made of silicon microstructures while the signal processing functionality is achieved by appropriate electronics.

Despite the fact that all these parts are often based on silicon technology (sensors and actuators can also be built using other materials, e.g. ceramics) microstructure design methods and electronic design methods are quite different. The microstructure engineer mainly designs new three-dimensional devices while the electronic designer connects well-known devices (e.g. transistors) or groups of devices (standard cells) together to build the desired functionality. Due to the very high prototyping costs, simulation plays an important role in either domain but the simulation techniques differ too. Analytical or finite-element (FE) techniques are used for microstructure simulation while electrical (SPICE-like) simulation techniques are used for analog electronics and event-driven (e.g. VHDL) simulation techniques are used for electronics.

This situation is satisfactory as long as each component of a microsystem can be designed independently starting from very precise specifications. In practice, however, the specifications are not precise enough and some parts must be redesigned when the prototypes are finally put together. Consequently, a more global design approach must be followed. In particular, we consider that system-level simulation of the microsystem should be performed using models of the different parts described at various abstraction levels according to the successive design steps. A test bench as well as external parts should be included in the simulation too.

The MicroSIM concept we present in this paper precisely aims at providing a single specification and simulation environment for microsystems which may contain sensors, actuators, external parts of various nature as well as electronics and a test bench. First, the system is described as the interconnection of high-level models of the components. This way, the feasibility of the microsystem can be demonstrated and the specifications of the different parts can be set up. Later, the simplified models can be replaced by lower-level models of the parts which have already been designed and system-level simulation can be used again to validate the design with the same test bench.

When models of various abstraction levels are present, we talk about *multi-level* simulation. When signals of various nature (e.g. electrical, mechanical, etc.) are involved, we talk about *mixed-nature* simulation. When analog models and digital models are simulated together, we talk about *mixed-mode* design.

In the next section (II), we present our microsystem simulation approach in greater detail. Then, in section III, we review some partial solutions already developed by partners of this project or by other authors. In section IV, two application examples are given that deal with particular microsystems, including sensor and actuator modeling and control part specification. In section V, we discuss the validity of our approach based on the experience gathered while studying these application examples. Finally, in section VI, we draw conclusions.

II. THE MICROSIM APPROACH

As already stated in the previous section, the aim of MicroSIM is to offer to microsystem engineers an integrated simulation environment which can be used during the whole development of the microsystem. We will now review the simulation needs and the various models to develop during microsystem design. The first step is system specification. We explain which models are necessary at this point and how we obtain them. Then microstructure parts and electronic parts are developed separately. However, simulation of the

whole microsystem must always be possible, eventually using new models of the newly designed parts.

System Specification

In a first design step the user will simulate the microsystem at a high level of abstraction, the aim of this simulation being rough architecture decomposition, architecture validation and component specification. Additionally, this description can be used to demonstrate the feasibility of the system to non-specialists: managers, marketing, but also experts from different disciplines. Typical components are sensors, actuators and signal processing part which can be divided, e.g., into analog interface, analog to digital conversion, digital signal processing, control logic, power supply.

The models which will be developed here are behavioral models of all the components involved as well as behavioral models of optional external parts.

Additionally, a test bench can be developed as a set of *physical* stimuli which state for input signals of various nature. This test bench, once completely defined, will be kept unchanged during the whole design process and will hence allow users to compare simulation results at various design steps.

The simulation environment must therefore be able to handle mixed-nature signals and it must include a mixed-mode, mixed-nature behavioral modeling language.

Behavioral Modeling

We review here the different models which are necessary to system specification and how they can be obtained. In a first step the behavior to model must be defined using appropriate methods and tools. In a second step, this behavior must be coded in a description language compatible with the simulation environment. Alternatively, the models are described in various environments and co-simulation is used, if available. However, as co-simulation could not be widely experimented, we concentrate on simulation solutions based on Hardware Description Languages (HDL) and electronic simulators.

Each behavioral model has a set of parameters which values can be set by the user in order to tailor the model to a particular application. During system-level specification, the parameters are used to experiment several solutions. Once a satisfactory solution has been selected, the corresponding parameter values become part of block specifications which are then taken as starting points for the particular block design process.

- *Electronic signal processing parts.* Here, the behavior to model is the desired functionality of the block. Several methods and tools exist for the development of behavioral models in the electronic domain. The models can be developed either using general purpose tools like MATLAB® or SIMULINK™ or using dedicated electronic CAD tools – e.g. SPW™ for digital signal processing, SpeedChart™ [3] for sequential machines, ABSynth [4] for analog functionalities. Digital models will then be expressed in VHDL while analog models will be expressed in VHDL-AMS – the analog and mixed-mode extension of VHDL – or HDL-A. This translation can be automatic or manual depending on the tools used. Typical parameters can be electrical (e.g. impedance, gain) or architectural (e.g. bus width, sample frequency).
- *Sensors and actuators.* At system level, these parts are seen as analog functionalities. Consequently, they can be modeled starting from the desired functionality and according to modeling methods developed for analog electronics and described above. In many practical cases, However, the type of microstructures to use is chosen very early in the system definition phase. Therefore, sensor and actuators can also be modeled starting from their particular structure and deriving characteristic equations analytically according to physics. The parameters are internal physical quantities like mass or damping coefficient. In the future, we hope to have behavioral models with geometrical dimensions of the microstructures as parameters.
- *External parts.* These elements are given by the environment in which the microsystem must work. The signals are external physical quantities like torque or temperatures.

Post-Design Modeling

After the global architecture has been successfully simulated, the various component models can serve as specifications and the actual design of the different components can begin. As the subject of this paper is simulation of microsystems, we do not go into detail of electronic or microstructure design. Rather, we review the type of information we get after design and how we can build new component models and integrate them in our system-level simulation.

- *Digital electronics.* The design process transforms – either manually or automatically – a high level behavioral specification into a detailed low-level structural description of the component. The leaf cells of the description are typically logic gates. If the simulation environment covers multi-level modeling and simulation – like VHDL does – the new structural models can be used directly in system-level simulation.
- *Analog electronics.* Here, the design process also results in a structural description of the blocks, typical leaf cells being now transistors, resistors, and capacitors. Theoretically, these new low-level structural models could also be used for system-level simulation. In practice, however, as the transistor models used in electrical simulation are quite complex, analog multi-level simulation is limited to small size descriptions (up to some hundreds of transistors). Consequently, we must go on with behavioral models of analog electronics for system-level simulation. Numerical values of the parameters, however, are extracted by detailed electrical simulation of the designed analog cells and the behavioral models are back-annotated accordingly.

- *Microstructures*. The design process results in dimensioned plans of the microstructures. Finite-element modeling and simulation are used extensively to verify the behavior of the devices. As we cannot couple behavioral simulators and FE simulators yet, we will also resort to behavioral descriptions of the microstructures in system-level simulations. Two possibilities exist: either FE simulations are used to extract numerical values of the parameters of the behavioral models or some new behavioral models are derived from FE simulation curves (e.g., piece-wise linear models). The calculation of macro-parameters (used in system-level lumped-parameter behavioral models) is performed using a parameter extractor tool implementing spatial integration of nodal or element degrees of freedom.

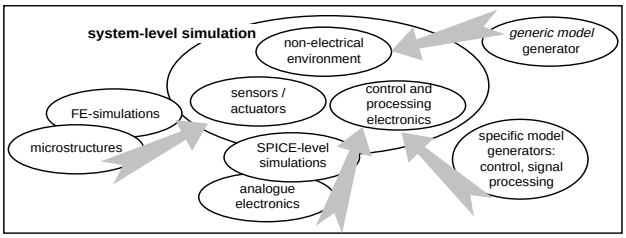

Fig 1: Mixed-nature simulation concept

Figure 1 illustrates the approach: various models originating from different domains have to be integrated in the same mixed-nature, mixed-mode, multi-level simulation environment.

Current Status and Further Requirements

In the previous paragraphs, we presented a general view to our approach. In practice, the situation is not developed that far. In most cases the designers do not begin with system specifications but they rather build the signal processing part around an existing microstructure and no interaction exist between electronic design and micro-structure design.

Some practical problems also occur while trying to implement the approach. First, a modeling and simulation language which covers all the desired signal natures and description levels must be selected. Second, the ultimate CAD system should include a library of detailed microstructures models as well as libraries of electronic models to make them available for reuse. Some generic models must be provided and additionally sets of *real-life* parameter values – extracted from actual components – should be included too. This database will allow users to follow a top-down design approach, eliminating in a wide extent the need for expertise at the device level. Third, simulation and design environment – based on existing design frameworks – will be extended with a user-friendly interface and standard output formats.

III. RELATED WORK

Previous Work Done by the MicroSIM Partners

Modeling of digital devices using the standard Hardware Description Language (HDL) IEEE-1076 VHDL as well as the graphical specification and automatic generation of such models have already been covered [2,3]. Similarly, the graphical specification of analog behavioral models and automatic coding using an analog HDL was presented in [4]. At the same time, partners worked on lower-level simulation and on parameter extraction for both analog electronics [5] and micro-structures [6].

Other Related Work

Powerful simulation tools exist for microelectronics, ranging from process simulation over device simulation to circuit simulation. For microstructures, in turn, only a few packages have been developed. These tools focus mostly on specific sensor [7-9] or actuator types. They use either analytical approaches or the finite element method to simulate the output characteristics of specific sensors as a function of the physical stimuli (pressure, temperature, humidity, magnetic field, ...). All these tools dispose of menu driven interfaces offering access to a database of material parameters and interfaces with other commercial software packages.

However there is currently no description language or simulation environment for microsystems containing at the same time sensors, actuators, electronics and signal processing units. This lack of CAD support hinders the diffusion of cost and time effective development methods for microsystems. Therefore, all these isolated results now have to be gathered in order to develop a complete microsystem design environment.

Choice of a Simulation Environment

To choose a simulation environment, we take into account the fact that, usually (but not exclusively [1]), microstructures, once successfully tested, are no longer modified. Electronics, in turn, are frequently tailored to specific applications: off-the-shelf sensors and actuators are used in conjunction with application-specific electronics. For current applications, a multi-level simulation facility will hence be more important for electronics than for micro-structures.

The specifications for a simulation environment become (i) support of modeling and simulation of devices of non-electrical nature, (ii) support of models provided by specific programs (e.g., control, numerical filtering), and (iii) based on an existing CAD environment for electronics.

Currently, Mentor Graphics Falcon Framework is used. It includes notably a schematic entry tool (Design Architect) as well as a mixed-mode simulator (Continuum) and can be enhanced by custom contributions [4].

IV. APPLICATION EXAMPLES

In the following, we present two typical microsystem examples, first an electrostatic wobble micromotor, then an active vibration damping system based on piezo transducers.

The wobble electrostatic motor

The wobble electrostatic micromotor [10] shows a strong coupling between its mechanical dynamics and the drive electronics. It consists of a disc shaped rotor of 2 mm diameter, resting on a central pivot, and a series of radial electrodes deposited on a substrate (fig. 2, right). LEG-EPLF developed a high-voltage digital control ASIC to drive the motor (fig. 2, left) [11].

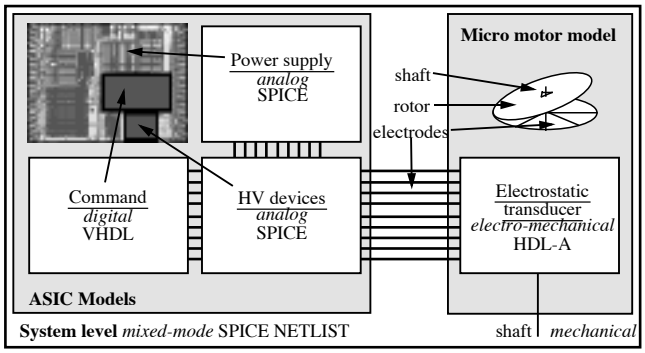

Fig 2: Schematic view of the microsystem composed of the ASIC drive circuit and the electrostatic planar wobble motor

The ANSYS™ finite element software was used to solve for the electrical field in the air-gap between stator and rotor. The electrical field is integrated over the rotor (tilted disc) to obtain torque and rotor-electrode capacitance as a function of the angle between the rotor and the active stator segment using *pxt*, a numerical parameter extraction tool for finite elements [13].

The resultant piece-wise linear torque and capacitance macro-models make a complete abstraction of the geometry and material properties of the constituent parts of the device. Behavioral models for the torque and capacitance functions are generated and integrated in a HDL-A model containing the motors mechanical equations.

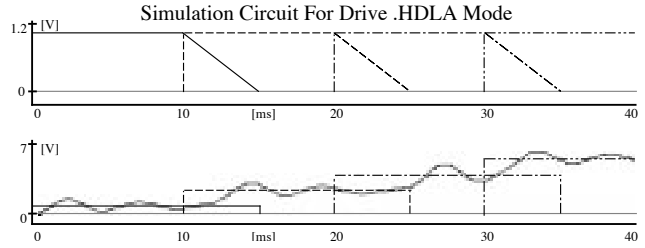

Fig 3: Transient simulation of the wobble motor's dynamics.

Digital and analog models of the electronics are combined with the physical device model of the actuator, in order to take into account the coupling between the drive electronics and the dynamically varying capacities of the drive electrodes. By varying the drive electronics and the shape of the drive pulses, motor performance and behavior was improved. Figure 3 above shows a typical simulation result. The upper graph shows the voltage pulses generated by the drive electronics on consecutive electrodes. The graph below shows the rotor (oscillating line) following consecutive electrodes (stepped lines).

One of the problems facing the designers was the need to prevent the rotor from slipping, which would result in unpredictable performance, as no position-feedback is present. The simulations showed that the usable output torque could be increased five-fold by using asymmetrical voltage pulses (to limit rotor slip) and an optimum number of stator electrodes (to limit output torque variations) [10].

Active Damping of Pressure Waves in an Aluminium Rod.

In order to damp actively pressure waves in an aluminium rod, piezoelectric ceramic discs have been incorporated to cover both the sensor and the actuator functionality in a feed-forward closed loop, a typical mechatronics system [12].

In our test set-up, an actuator A_1 generates vibrations at the left end of the rod (fig. 4). A first sensor S_1 detects these vibrations. Towards the middle of the rod, there is a second actuator A_2 that, ideally, works in counter-phase such that it absorbs vibrations from the left: the second sensor S_2 should not measure any vibrations. The challenge is to determine – and to realize in electronics hardware – the transfer function H_c of the feed-forward control loop, possibly completed by a feed-back branch from the second sensor. Obviously, there is again a strong coupling between mechanics and electronics.

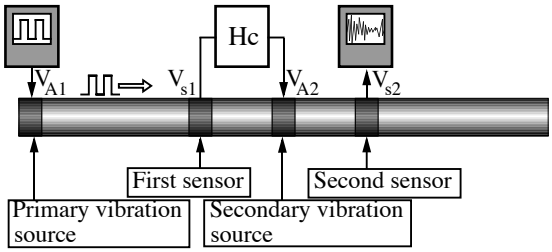

Fig 4: Active damping set-up

According to our approach, we first develop HDL-A models for the different elements of the microsystem: rods, sensors, actuators, and electronic control.

A generic model for the non-electrical elements has been written in HDL-A and simulated with a first set of parameters. The mechanical elements have been modeled as finite elements (e.g., masses, springs), the piezos as finite elements and controlled sources. Then, the model parameters are to be adapted to match as well as possible simulation results obtained by measurements. This matching process as well as the model validation process – crucial to the global simulation approach – needs much attention and, up to know, much assistance from expert FE users.

Thanks to these models, we can now use the simulation results to determine the transfer function H_c from the

individual transfer functions H_{ij} (Eq. 2) characterizing the outputs $V_{S1}(s)$ and $V_{S2}(s)$ in function of the two inputs $V_{A1}(s)$ and $V_{A2}(s)$ respectively (Eq. 1).

$$\begin{aligned} V_{S1} &= V_{A1} \cdot H_{11} + V_{A2} \cdot H_{12} \\ V_{S2} &= V_{A1} \cdot H_{21} + V_{A2} \cdot H_{22} \end{aligned} \qquad \text{(eq.1)}$$

$$H_{11} = \left.\frac{V_{S2}}{V_{A1}}\right|_{V_{A2} \equiv 0} \qquad H_{21} = \left.\frac{V_{S1}}{V_{A1}}\right|_{V_{A2} \equiv 0} \qquad \text{(eq.2)}$$

$$H_{11} = \left.\frac{V_{S2}}{V_{A2}}\right|_{V_{A1} \equiv 0} \qquad H_{11} = \left.\frac{V_{S1}}{V_{A2}}\right|_{V_{A1} \equiv 0}$$

With $V_{S2}(s) = 0$, we get the ideal transfer function H_c (eq.3) that allows for complete damping of the vibrations induced by $V_{A1}(s)$.

$$\begin{aligned} Hc &= \left.\frac{V_{A2}}{V_{S1}}\right|_{V_{S2} \equiv 0} \\ &= \left(H_{22} - \frac{H_{12} \cdot H_{21}}{H_{11}} \right)^{-1} \end{aligned} \qquad \text{(eq.3)}$$

We now are able to realize a HDL-A model of the H_c regulator and to simulate it together with the model that describes the behavior of rods, sensors, and actuators: the control loop can be closed.

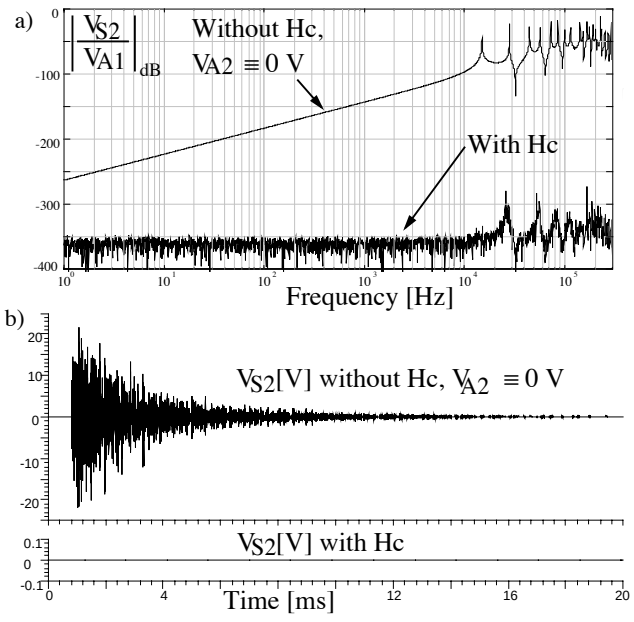

Fig. 5: Simulation results, with and without H_c regulator: a) AC behavior, and b) impulse responses of the system.

Figure 5.a shows the AC simulation results obtained. As expected, the feed-forward control loop allows to reduce in an important manner – more than 100 dB – the vibrations detected on sensor S_2. Ideally, we should have found V_{S2} reduced to 0 but some residual vibration – to be interpreted as simulation noise – remains.

The same way, the impulse response has been simulated, again with and without the regulator (fig. 5.b). The H_c regulator developed damped totally the vibrations introduced by actuator A_1.

Once the models of the rods, the sensors, and the actuators validated, the conceptual problem is solved and we can concentrate on the implementation of the H_c regulator.

For a realization in analog electronics, a circuit implementing the H_c transfer function can be developed. The corresponding model can then replace the initial behavioral Hc model and the original bench tests can be conducted.

If we chose to realize the H_c regulator with mixed electronics – and if the transfer function is causal and realizable – we can pass from the continuos domain (Laplace) to the time discrete domain (z-transform), e.g. using the bilinear transformation. This way, we get $H_c(z)$ we could realize as VHDL or HDL-A models. Obviously, the $H_c(z)$ regulator has to be completed by low-pass filters (anti-aliaising) and A/D and D/A converters (fig. 6).

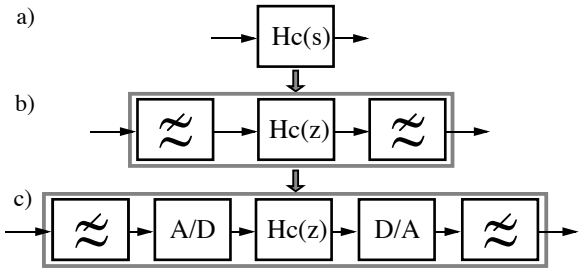

Fig. 6: Possible refinement steps during the development of the H_c regulator electronics

Again, the implementation of the H_c regulator can be tested in the initial test-bench at each level of refinement, allowing hence for easy comparison of the expected results with the results we obtain at each stage.

Note that further refinement potentially leads to problems beyond the scope of this paper, e.g. (i) data representation, (ii) finite precision arithmetic, and (iii) implementation in software on processors.

V. Discussion of First Results

The results of the first experiences, but also discussions with many partners showed us clearly that the global simulation approach, combining models from various domains, corresponds to a real need.

The use of the global simulation approach and the corresponding tools also helps the designer to test many what-if cases before costly prototyping and is indeed mandatory when searching for a global optimum of system performance.

Modeling and simulation of the wobble electrostatic micromotor enabled large improvements: taking into account the coupling between the mechanical and the electrical domain

through system-level simulation., the motor's performance could be increased by a factor of five.

The example of the active damping of pressure waves in an aluminium rod showed again the strong coupling between system-components, a behavior that is representative for the constraints present in most of the micro-electro-mechanical systems (MEMS). The fact that the models had been generated, instantiated and finally simulated in a common environment helped us to clarify many problems that did either not show up or where tackled in various, domain-specific ways when specialists of the various domains met. Once confronted with the simulation results they where forced – but also motivated – to solve the global problem in common.

Nevertheless, this second example also showed clearly two important limits of the approach: (i) the generation of models and (ii) the validation of the models. Both problems must still be handled in collaboration with specialists of the respective domains before the models can be handed over to system level users, possibly in the form of libraries.

Nevertheless, we firmly believe that the methodology and software tools presented will more and more find application in the field of mechatronics. We are also convinced that a broader use of this methodology can lead to an extended use of microstructures and a simplified assembly with the corresponding electronics.

VI. CONCLUSIONS

In this paper, we present an approach to handle the problem of integrated product simulation and design. We propose an approach based on behavioral models of mixed-nature (mechanical, fluid, electrical, etc.) components that allows the overall behavior of a micro-system to be simulated before any realization is done. During successive steps, the system will be refined – in particular electronics that is most probably to be adapted to specific applications – while maintaining the initial test conditions. Global system optimization is thus achieved.

VII. ACKNOWLEDGMENTS

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