Approach to Microsystem Design

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Abstract: - Microsystems concentrate all progressive element and technologies of microelectronics. The paper describes the approach to the design of a simple microsystem structure on the one side and smart microsystems on the second side. There is proposed a concept of models on the different levels in the paper. The design of microsystems is a complex of various energy domains. Electrical models are solved using tools for solving electrical circuits. The equivalence of parameters between electrical and mechanical domains is very often used in the design of a simple structure. The highest level creates the system models, in the lowest level there is the physical model and material models. Analytical and numerical models are very often used. SUN workstation and PC network as hardware are used. Professional software tools (Cadence, Spice, CoventorWare) serve for microsystem design. Some design examples are presented in the paper.

Key-Words: - Microsystems, design, energy equivalence, communications

1 Introduction

Sensors and actuators become basic microsystem elements working in real surrounding environment. Solving microsystem structures enables us to acquire qualitatively better properties usable in all areas of human life. In the resulting arrangement, the microsystems are realized as "micro" using suitable and available technologies. Some of the technologies are often developed directly for this purpose.

For modelling microsystem properties, it is possible to use "macromodels" as well. They can be realized e.g. using available electronic elements. With mathematical support and using analogy between physical quantities, microsystem model can be developed that are very close to real microsystem with respect to their properties.

Problems of exact data acquisition from sensors and data transmission to control elements or actuators are very topical in many areas of non-electric quantities processing. Successive integration of designed systems on one or more chips improves reliability and usability, and decreases consumption of electric energy for system feeding. A system aimed at use in control circuits, having sensor inputs, actuator outputs and exploiting software algorithms, can reach very good parameters. Systems used in interdisciplinary areas are known as microsystems nowadays. As an example there is presented a macro-model structure of an intelligent microsystem with contactless communication between measuring sensors and control unit – see Fig.1. The structure can be modified for other energy spaces.

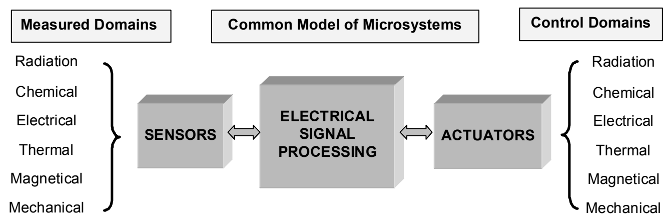


Fig.1 Conceptual structure of an intelligent microsystem

2 General microsystem model

We have designed a model structure of an intelligent microsystem with contactless communication between measuring sensors and control unit – Fig.2. The topic of the work is the design of concept and structure, realization of hardware model of an intelligent microsystem whose structure can be modified for other energy spaces (chemistry, biology, etc.).

The system consists of individual functional blocks. Activity control and certain level of intelligence are accomplished by the central control unit. Sensor blocks represent electronic converters where there is non-electric quantity on the input and the output is in digital form suitable for processing in the central control unit. Actuators represent converters of digital control signal to signal controlling corresponding energy domain. Mutual communication inside the microsystem is performed on the communication bus.

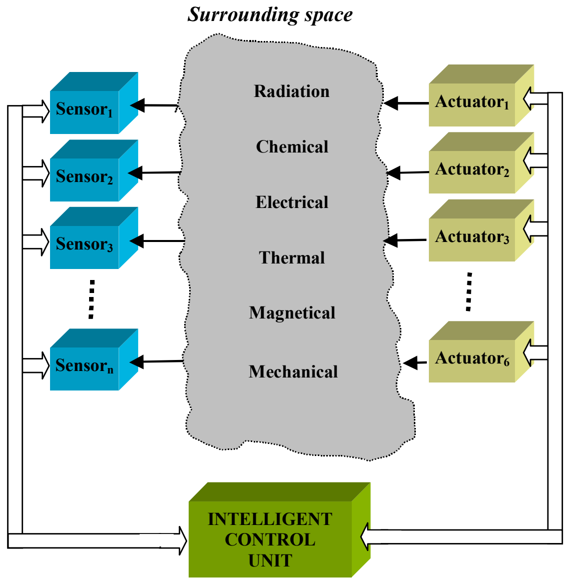


Fig.2 Concept structure of intelligent microsystems

3 Hard and soft models of temperature control System

Ideative model. At first the student creates an ideative model of a microsystem with input information, output functions, and inner logical functions.

Soft model. Further Stepp is realization of the SOFT model of the microsystem using PC and libraries of electronic components and blocks. For special microsystem blocks it is necessary to use either existing blocks or the student has to define these special blocks. In this model it is possible to simulate simple functions using means for analysis of electronic circuits and systems. Realization of micromechanical elements in this model is based on electrical and mechanical, or possibly further analogies. For realization of the SOFT model in this phase simplified electrical and non-electrical functions are considered so that it is possible to realize them in a simple way.

HARD model. Realization of HARD model is a successive step and is used for verification of basic functions of the designed SOFT model. It is possible to use available elements for realization of the HARD model. This model illustrates characteristics and behaviour of the designed microsystem model. It is instructive for education, it is possible to demonstrate its behaviour and basic characteristics. There are close connections between SOFT and HARD models. The students can develop a real functional model.

Design of microsystem. Design of the microsystem is the most difficult part and follows after previous steps. Micro-models are developed from these macro-models according to the rules for design of integrated microsystems (technology, materials, software, etc.). Macro-model properties are compared with simulated and modelled properties of real microsystem. For these purposes, suitable tools are utilized (MEMCAD, CADENCE, HSPICE, etc.) [1]. In the paper there are presented examples of realized HARD macro-models.

3.1 Model of temperature control system

The model considers activity in temperature domain. Activity control and certain level of intelligence are accomplished by the central control unit. The control unit controls switching of the actuator, communicates with sensor units, control keyboard and informs about system state using alphanumeric display.

Communication of control unit is performed via serial communication bus. Communication of each sensor unit with the control unit is done using radiofrequency method. Mutual communication inside the microsystem is performed on the communication bus – see Fig.3.

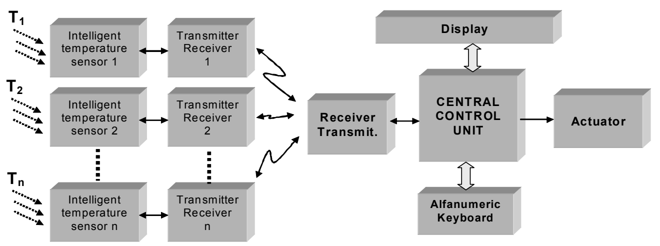


Fig.3 Macro-model of smart temperature control system

Sensor blocks represent electronic converters where there is non-electric quantity on the input and the output is in digital form suitable for processing in the central control unit. The sensor unit is represented by the temperature/electric signal converter. Integrated temperature sensor is controlled via this bus and information on current temperature is transmitted in this way as well. Actuator(s) represents a converter of digital control signal to signal controlling corresponding energy domain. Software controls activity of the whole system according to defined functions.

3.2 Sensor for wireless communications

The core of the sensor unit is represented by the temperature/electric signal converter [2]. For realization of the model, integrated temperature sensor LM76 has been used. This circuit has an integrated A/D converter with control serial interface I^2C. Integrated temperature sensor is controlled via this bus and information on current temperature is transmitted in this way as well. Required defined sensor function is set by recording data into internal registers. Information on current temperature [3] is acquired by reading content of temperature register. Implicit values are recorded into registers during rise time of supply voltage. Access to individual registers is controlled via communication bus. Connection of the intelligent sensor unit, is shown in Fig.4.

Fig.4 Connection of intelligent sensor unit

Setting of internal circuit functions and reading information on measured temperature is performed through serial communication bus I^2C. The bus is two-way two-wire with serial data transmission between individual circuit parts. Data are transmitted using data line (SDA*),* clock line (SCL) is used for transmission of clock signal. Line outputs consist of transistors with open collectors – Fig.5. In the given time moment, only one MASTER circuit participates in communication through MASTER/SLAVE bus. The MASTER circuit addresses one of the subordinate SLAVE circuits. Data bit is transmitted during every clock pulse.

The circuit of the temperature sensor is completed with a communication circuit (RF receiver/transmitter) for wireless communication with working frequency 433.92 MHz. The circuit enables two-way transmission of digital data using half-duplex radiofrequency operation with fast switching between transmission and reception (< 100 ms) and encoding of carrier TTL level.

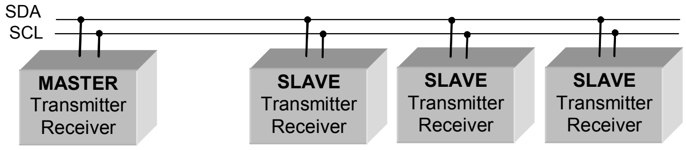


Fig.5 Basic connection of communication bus I^2C

3.3 Software control

For programming of required system functions, C51 language has been selected. Software controls activity of the whole system according to defined functions. In the model, the day has been divided into 6 time intervals of different length. In each time interval, it is possible to specify beginning and end time of that interval, number of the sensor that will be communicating. In this way it is possible to set individually each day in week.

In addition to these basic functions, the system enables to perform further functions, e.g. search for maximum and minimum of followed quantities, system control according to these extremes, etc. The system activity is independent on user operations (e.g. system configuration). This activity is enabled by so-called multitasking that is very demanding from the point of view of processor and other system tools. In our environment, we have used algorithms of creating ***"transit"*** function that satisfies condition of independence of system activity. Basic principle lies in automatic finishing of individual functions in case of their "idleness". It enables to perform other system functions. Individual functions are called repeatedly (in a cycle), their execution time is relatively short. Resulting program behaves as a very simple "multitasking" system.

It is necessary to use global variables for each function to save current function state and possibly further values. That puts higher demands on system data memory.

3.4 Results

Designed model of the temperature microsystem has been realized from discrete elements - hard model. Basic system functions have been verified on the functional model, especially precision of transmitted information on measured temperature in dependence on space geometry. Information on measured temperature displayed by the system has been compared with data from precise thermometer. The results are displayed on Fig.6. ΔT indicates difference between displayed data from the thermometer and system. Communication range has been determined in dependence on length of the antenna of communication module and geometry of obstacles in the space.

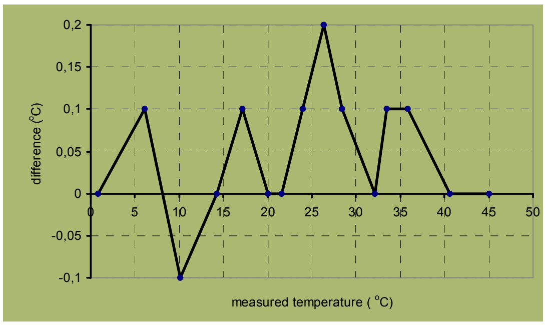


Fig.6 Difference between data from the thermometer and system

4 Equivalent models between different energy domains

Behaviour of a sensor or sensor block can be described by differential equations whose form is dependent on physical nature of corresponding sensor or sensor block activity [4]. Three basic function types exist for description of this behaviour. The functions describe the relation between input and output (zero-order, first-order, second-order). Mathematical modelling of a sensor is a powerful tool in assessing its performance.
The mathematical models are utilized for equivalence generation. Physical laws are applied to these models. Results are the models with simple lumped parameters. Mechanical and thermal elements can be converted in this way to equivalent electric connection. For solving the electric model, well-known and elaborated methods for electric circuits can be used. For the mechanical components, Newton’s second law is used. We can create mechanical model of the system - Fig.7.

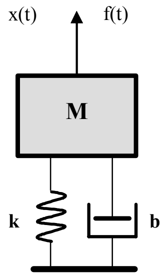


Fig.7 Mechanical system

The system in Fig.7 can be described as

$$M\frac{d^2x}{dt^2}+b\frac{dx}{dt}+k\cdot x=F^{'}(t) \qquad (1)$$

where *F’(t)* is excitation force, k is rigidity of the spring, b is the coefficient of damp, M is a solid element without elastic and damping properties [5]. The equation can be modified. It is possible to find known equivalence between the differential equation describing behaviour of serial or parallel resonance circuits and differential equation describing behaviour of mechanical structure. Serial resonance RLC circuit can be described by the equation

$$L\frac{di}{dt}+R\cdot i+\frac{1}{C}\int i\cdot dt=u(t) \qquad (2)$$

We introduce the substitution $\frac{dx}{dt}=i$ into the equation (1) and we get the equation

$$M\frac{di}{dt}+b\cdot i+k\int i\cdot dt=F^{'}(t) \qquad (3)$$

Comparing both equations we get equivalence of mechanical and electrical parameters – see Table 1. For parallel resonance RLC circuit, the equation holds

$$C\frac{du}{dt}+\frac{1}{R}\cdot u+\frac{1}{L}\int u\cdot dt=u(t) \qquad (4)$$

Introducing substitution $\frac{dx}{dt}=u$ into the equation (1) we get

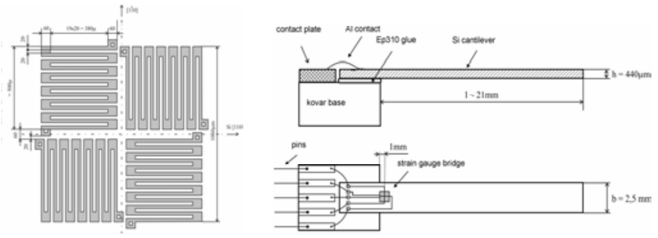
$$M\frac{du}{dt}+b\cdot u+k\int u\cdot dt=F'(t) \qquad (5)$$

Comparing parameters of both equations we get equivalence presented in Table 1.

Table1 Mechanical and electrical analogies

Mechanical	Analogies	Electrical	
Mass M $F'=M\frac{d(v)}{dt}$	M ≡ L, M ≡ C	Inductor L $V'=L\frac{d(i)}{dt}$	Capacitor C $i'=C\frac{d(V)}{dt}$
Spring k $F'=k\int v\cdot dt$	k ≡ 1/C, k ≡ 1/L	Capacitor C $V'=\frac{1}{C}\int i\cdot dt$	Inductor L $i'=\frac{1}{L}\int V\cdot dt$
Damper b $F'=bv$	b ≡ R, b ≡ 1/R	Resistor R $V'=Ri$	Resistor R $i'=\frac{1}{R}V$

Presented models can be used for the design of force sensor. The base of sensor is cantilever beam with piezoresistive layer as a strain gauge. Cantilever with geometric layout can be equivalently replaced with a system with spring, load, and damp of the system. Example of a designed strain gauge geometry with long piezoresistor for connection to full bridge is shown in Fig.8a). Measured force is effective on the free end of the cantilever perpendicularly to its axis and causes its deformation. Strain gauges are located in the place where the maximum mechanical tension is.



a) b)

Fig.8 Geometry of Si strain sensor a) strain gauge, b) Si cantilever with piezoresistors

Geometry of Si cantilever with piezoresistors and fixation on kovar base is shown in Fig.8b). Length of the cantilever (to the point of fixation) is *l=21 mm*, width *b=2.5 mm* and thickness *h=440 µm*. Mechanical tension in place of implanted strain gauges is [1]

$$\sigma_x = \frac{3E \cdot y_0 \cdot h \cdot x}{2l^3} = \frac{6F \cdot x}{b \cdot h^2} \quad (6)$$

where E is module of Si elasticity $E=1.69.10^{11}Nm^{-2}$, y_0 is cantilever bend, h is cantilever thickness, l is cantilever length and F is force effective on the free end of the cantilever. Maximum load and bend of the cantilever results from maximum allowed mechanical tension of Si σ_{DOV}. The equation can be written as [5]

$$y_{\max} = \frac{2 \cdot \sigma_{DOV} \cdot l^2}{3 \cdot E \cdot h} \quad (7)$$

where g is gravitational acceleration.

At simplified design of Si cantilever we assume ideal fixation of Si cantilever to the base. We assume further that the coefficients of thermal expansibility of Si and material of the base are identical [6].

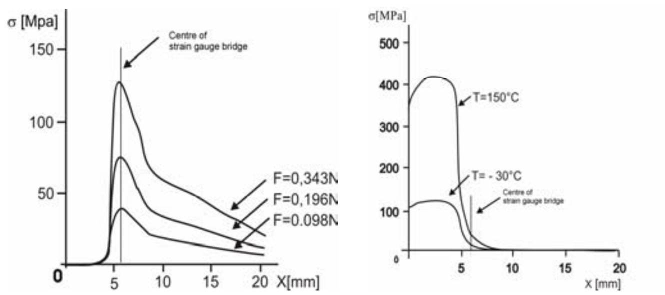
For successful simulation, it is necessary to input all material constants correctly. There have been realised following simulations.

Mechanical simulation. The simulation calculates bend of the cantilever and value of mechanical strain on the surface of the cantilever caused by this bend. The input values are coordinates and magnitude of the vector of effective force.

Piezoresistive simulation. The simulation calculates magnitude of voltage on meander at constant current in dependence on cantilever deformation caused by effective force. The resistance of meander can be calculated from the voltage and known current. The resistance is proportional to surface tension. The surface tension has been acquired as a result of mechanical simulation. Inputs are piezoresistive coefficients and output files of mechanical simulation.

Thermal simulation. Results of this simulation are data on mechanical strain arising in connection of cantilever with base due to different thermal expansibility of material of base and Si at temperature changes. Input values are coefficients of thermal expansibility and environment temperature. For simulation it is assumed that the thickness of connecting layer is negligible in comparison with the thickness of Si cantilever.

Results acquired from performed simulations show distribution of mechanical tension along x axis of the cantilever with acting force on the end of the cantilever as parameter – see Fig.9a). The graph shows that the strain gauge bridge is located in the place of the greatest mechanical strain of the bridge.



a) b)

Fig.9 Simulation of distribution of mechanical tension

Piezorezistive simulation enables to calculate dependence of resistance for different concentrations of impurities.

For *thermal simulation* it is assumed that thickness of glue layer is negligible in comparison to thickness of Si cantilever. Fig.9b) result of simulation of dependence of mechanical tension on distance in x axis with temperature as parameter is shown.

5 Design flow

The design of microsystems can be realized in several forms with corresponding time series [1]. Ideative model of microsystems can be created. The model has input information, output functions, and inner logical functions. Further step is realization of the SOFT model of microsystems using PC and libraries of electronic components and blocks. In this model it is possible to simulate simple functions using means for analysis of electronic circuits and systems. Realization of micromechanical elements in this model is based on electrical and mechanical, or possibly further analogies.

Realization of HARD model is used for verification of basic functions of the designed SOFT model. This model illustrates characteristics and behaviour of the designed microsystems model.

Design of microsystems is the most difficult part. Micro-models are developed from these macro-models (technology, materials, software, etc.). Macro-model properties are compared with simulated and modeled properties of real microsystems. For these purposes, suitable tools are utilized (MEMCAD, CADENCE, HSPICE, etc.) [4]. Simulation and design flow of microsystems on the different levels are illustrated in Fig.10.

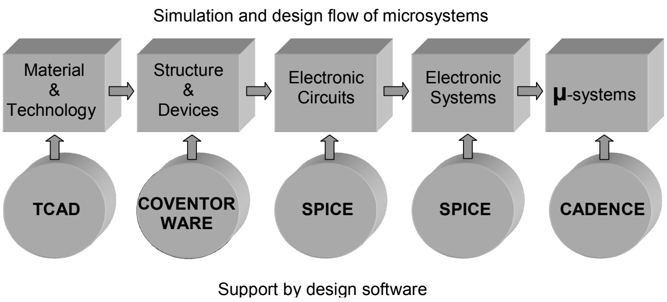


Fig.10Design flow of model levels

6 Conclusions

It is necessary to use models on system level for correct complex functioning of the designed MST. On lower levels, further types of models can be used: models on the level of individual energy domains, physical models, etc.. In design process, there can be used equivalent models that operate with quantities from various energy domains. A number of design tools (ANSYS, CoventorWare, MEMCAP, etc.) exist for modeling of structures and further elements of MST.

Modeling and simulation on various MST levels are utilizes for optima MST design. The work describes development of illustrative functional models of MST, simulation and modelling of real MST, comparison of properties of macro and micro models, utilization of tools for design and simulation of integrated circuits and MST, development of macromodels for electrical, mechanical, thermal and chemical energy domains, real function of macromodel and its application. Presented principle of development of macromodels of MST enables to bring this topic closer to educational process.

7 Acknowledgements

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