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METHODS AND MODELS FOR COMPUTER AIDED MEMS DESIGN

In this paper an analysis of MEMS design features has been conducted. At the basis of that analysis an implementation of algorithmic aspect in MEMS design is proposed.

Keywords – microelectronics, MEMS, CAD.

1. Introduction

The beginning of XXI is characterized with intensive development of interdisciplinary research domains, what caused a new type of devices appearance, they are: microelectromechanical; systems (MEMS) [1-7].

First of MEMS has appeared due to integration of microelectronics and micromechanics technologies. Such join allows receiving microdevices, where on one semiconductor crystal, in addition to static elements (integral cirquits), are also placed movable microdevices (actuators).

Such type of integral devices has a number of advantages in comparison with real world devices: they are more reliable, cheaper, lighter; small power energy, integration of scientific domains has a synergetic nature, batch fabrication technology and etc.

MEMS are very complicated devices, therefore during their design and simulation we can do without computer aided design systems and conformable methods, algorithms and mathematical models [8-9].

2. Structure of MEMS

Basic MEMS structure is shown on fig. 1. It includes input transducer, microprocessor, output transducer, analog to digital converter (ADC) and digital to analog converter (DAC). [10].

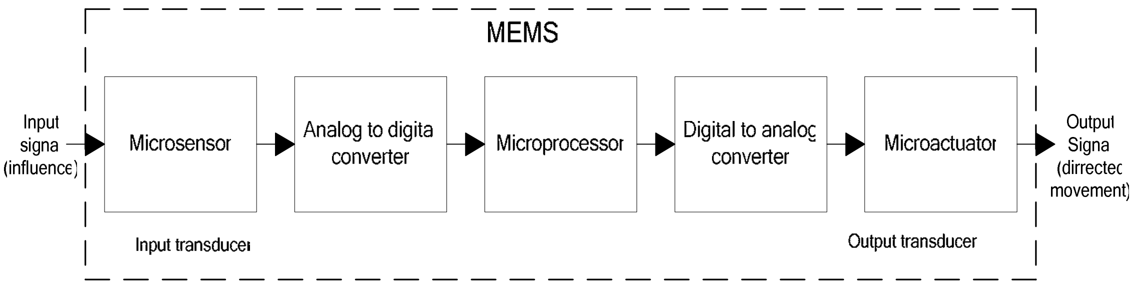

Fig.1. Basic structure of MEMS

Input transducer is intended for sensing of changes or influence of environment on the system. As a rule, microsensors are referred as input transducers. Such devices convert, for example, pressure, stress or displacement changes into electrical parameter changes, which can be processed by microprocessor. In many microprocessors, as a sensor output electrical parameter can be used resistance, electrical capacitance, frequency, voltage, current etc. Since microprocessor can not directly process analog value, then after microsensor analog to digital transducer must be used. From which already digital signal goes to microprocessor. Microprocessor processes received data accordingly to previously defined algorithm and put it at the digital to analog converter. DAC transforms code to analog signal, which directly is given to output transducer. As an output transducer stands actuator – microdevices, which transform electrical energy into some other type of energy or into directed movement.

3. Classification of MEMS and its components

Processes of investigation, engineering, simulation and design are imprescriptible connected with processes of design objects classification, what allows more effectively organize process of their design and modeling.

Any classification is tightly connected with criterion or several criterions. If, as a classification criterion, type of element, which performs energy transformation from one state to another, is selected, then all components of microelectromechanical systems can be divided into three basic groups. Therefore, first group is composed from microsensors, second – from microactuators, and third group is composed from representation devices, which are assigned for representation of changes in the environment, naturally, that changes must be fixed by microsensor (as a rule, such group of element do not perform mechanical movements).

There are a specific group of microdevices, which do not perform nor any energy transformation from one state to another, nor any movements, microlens, microchanals of hydraulic elements, micronozzels are referred to them and are an inherent part of MEMS, specifically optical, fluidic, etc.

Due to presented MEMS elements types, all of them can be placed at single or several crystals. In first case we receive singlecrystal MEMS, in the second case- multicrystal (multichip). Approach for multichip MEMS elements connection is caused by difficulty of fabrication with one technology all of the three integral systems components. Sufficiently frequently all of three MEMS components are fabricated by different technologies with following placement at single or several crystals.

At the same time, MEMS can be divided into two big groups: autonomous and embedded. As an autonomous can be referred, for example, microrobots, microlabs on chip, and as embedded – system of airbag ejection in automobiles, system of ink drop ejection in printers and etc.

Due to input energy, the next classification of actuators with usage of electrical energy, fluid energy, thermal energy, chemical energy and other, is presented.

The next step defines which forces are used in actuators work. With the help of each type of energy some group of forces can be generated. So, for example, electrical energy allows generating two types of forces: molecular forces and magnetic field forces. Correspondingly forces allow designing two different types of actuators. In case of molecular forces we obtain three types of actuators: magnetostriction, piezoelectric and electroreological, and in case of electrical and magnetic field forces – electrostatic and electromagnetic actuators.

Presented actuators classification example allows to describe every from their parameters, which indirect influence on requirement specification parameters (RS) of MEMS.

Concerning to integral sensors, their classification can be performed due to the next basic criterions:

1. microsensor destinations (microsensor of pressure, humidity, force and etc.);
2. microsensor output steered parameter (capacitance microsensor, piezoelectric, etc);
3. physical processes, which are used in microsensors functioning (microsensor based on the piezo efect, microsensor based on magnetostriction effect etc).

4. Features of MEMS design and simulation

Improvement of microelectromechanical system fabrication technologies [8-10], grading up of their technical-operational characteristics, reducing of full introduction cycle nowadays is defined by a design process of integral devices automation and a technological process of their fabrication.

Modern process of MEMS design, with usage of the most modern technologies, demands synchronous optimization of technological process, construction of integral device and functional scheme. Therefore, CAD tools for MEMS are inherent part of integral devices modern fabrication process.

Simplistically, multilevel hierarchical design is used as design of microelectromechanical systems. Since MEMS design is tightly connected with fabrication technology, then at the lowest technological level will be situated (technological design), where technology of MEMS fabrication is designed. Taking into account that MEMS technologies are based on IC fabrication technologies and micromechanical devices technologies, than, as a rule, that technology is already completely developed (base technological process is used) and requires a few insignificant changes. But it should be noted, that design and research of new technologies for MEMS fabrication is very actively performed. Historically happened, that the biggest design centers use different technologies. Technologies used in USA based on IC fabrication technologies, and technologies used in Europe and Japan – on micromechanical fabrication technologies (LIGA, SIGA, etc.)[1].

The next (in dependence from refining level and complexity of design object their amount can be larger) levels are referred to structural design.

During MEMS design, in most cases, classical multilevel downward design [8-9] “up – down” and upward design - “down – up” are used. For example, “up – down” design supposes that, MEMS design is divided into solving separate subtask, they are: design of functionally completed MEMS modules (microsensors, microprocessor module, executing devices etc). The next design decomposition supposes dividing of microsensors and microactuator design tasks into elements design tasks. Those are tasks, connected with design of stator and rotor of micro engine, spring or power source of electrostatic microactuators. The next step of decomposition supposes dividing tasks of MEMS components design into tasks of integral devices elements design. Therefore, structural MEMS design scheme defines four design levels. First level is called system, second – functional, third – MEMS component design level, fourth - element.

Such MEMS design approach has a number of advantages, they are: more convenient work with more simple objects, possibility of performing simulation of functioning, verification and testing design results etc.

Methods of upwards design can be used in case, when it is necessary to design similar device and some components of this product, which are already partly or completely designed.

This kind of MEMS design every year is used more and more often, because of library of designed element became larger.

Nevertheless, design of microelectromechnical system elements series should be run in parallel, what allows speed up of some design levels. For example, design of microsensors, microactuators and control system can be run in parallel.

So, classical methods of upward and downward for electromechanical integral systems design are used and special attention should be paid to design in parallel, what is caused by features of interdisciplinary microsysytems.

5. Design aspects

As was mentioned before, MEMS design is based on IC design technologies, which includes three aspects of design: functional-logical, design and technological.

The feature of the MEMS design, especially autonomous, is functioning by in advance defined algorithms, which defines device work at the basis of input data.

Design of algorithms takes a huge time of MEMS design works. Therefore, in contrast to IC design, it is necessary to add forth aspect: algorithmic, which must be taken into account at each level of multilevel hierarchical system design. Adding of this aspect allows increasing of quality and efficiency of MEMS design.

6. System level of MEMS design

For solving problem of alternative solution set construction in MEMS design theory of AND-OR trees was applied [8, 9].

AND-OR tree, for MEMS structure design, is built due to mentioned before classification. So, at the upper level OR node is placed, which defines two possible type of MEMS, they are: embedded system or autonomous. Each MEMS type, correspondingly, includes some subsystems (sensors subsystem, actuators subsystem, processing subsystem, power subsystem). In according to development of this domain, a set of possible solutions grows up. This level is a node of type AND. For example, due to specificity of embedded MEMS, it includes three subsystems: sensor subsystem, actuators subsystem and data processing subsystem.

The next level includes node of type OR. Actuators subsystem may include one or several devices. Since their number is large, then we use only few basic devices, which are common for all groups of actuators. Sensors subsystem may include, as in case of actuator subsystem, one or several integral sensors. Power subsystem may include static (accumulator type) and dynamic (solar cells, power subsystem with piezoefect etc). Data processing subsystem may include digital, analog or neural network scheme. Each from which has its own advantages and disadvantages.

Fourth level includes node of AND type. Naturally, digital processing scheme necessarily must include such elements as ADC, multiplexer, MP, DAC, operative memory device (OMD) or permanent memory device (PMD) or one coupled with another. Correspondingly, analog scheme must include such basic elements: input stage, processing scheme, buffer scheme, multiplexer etc

For MEMS structure alternative solutions set usage of such rules are proposed:

- for single crystal MEMS it is necessary to use integral devices, which are fabricated by batch processing;
- multi crystal MEMS may be produced by different technologies;
- integral actuators, which parameters do not satisfy requirements of RS for MEMS, are excluded from consideration;
- integral sensors, which parameters do not satisfy requirements of RS for MEMS, are excluded from consideration;
- necessarily adding of element, designed by developer, into alternative structure;
- alternative solutions, which summary output parameters do not satisfy requirements of RS for MEMS, are excluded from consideration.

For alternative solution set formalization a special data structure was designed. Let's note a MEMS structure alternative solution set as M. Each of alternative solution will be noted as E_i, where $i = \overline{1, n}$. Then a set of alternative solution will have the next view: $M(E_1, E_2, ...E_n)$, where a power of set is equal n. Forming of each alternative solution is carried out due to rules defined before and AND-OR graph of possible solutions. Each of alternative solution is represented by a number, in which alternative structure of MEMS is enclosed.

Each alternative includes such information: code of MEMS type, a number of subsystem and their codes. Later, due to defined codes of subsystem, a number of devices in each subsystem and their codes are written. In case of availability of forth level elements in alternative and structure, a number of elements after device code is written, and then follows codes of used elements.

For the best solution selection from a set of possible solutions a method of branches and borders is used [11, 12].

Completely autonomous MEMS, in contrast to presented on fig. 1., may include *n* sensors, single microprocessor and *k* actuators.

For dynamic analysis of presented system structure a theory of colored Petri networks is used [13, 14]. In case of necessity of taking into account priority - correspondingly information should be added to the network, and in case of consideration a time parameter it is necessary take into account a time mechanism of colored network.

7. Functional level models of MEMS design

Mathematical models of the functional level of design have its own specificity and features. Particularly, as a rule, they include a systems of algebraic and common differential equations (CDE). Corresponded models do not demand huge wastes of PC resources, but, at the same time, precision of the output results is not high, what is completely enough at the current design stage.

Described mathematical apparatus may be successfully used for developing of functional level MM design of microelectromechanical systems.

For example, capacitance type accelerometer functioning, which construction is presented in work [1], can be represented by the reduced model, which is shown on fig.2.

By analogy with accelerometer construction, in reduced model m – defines seismic mass; F – applied force; k – spring stiffness coefficient; b – damping coefficient.

Functioning of presented before system is described by second order differential equations

$$m\ddot{X} + b\dot{X} + kX = F, \qquad F = F_a + F_e, \qquad (1)$$

where X - displacement; $\dot{X}$ - displacement speed; $\ddot{X}$ - displacement acceleration; F_a - mechanical force; F_e - electrostatic field force.

For electrostatic force value determination the next expression will be used [1]:

$$F_e = \frac{\varepsilon A U^2}{2(d-x)^2}, \qquad C = \varepsilon \frac{A}{d-x}, \qquad (2)$$

where C – electrostatic capacitance; A – plates area; U – applied voltage; d – initial distance between capacitor plates; ε - environment permittivity between capacitor plates.

For electrostatic resonator functioning analysis [15] at the functional design level reduced model will have the view as on fig. 3.

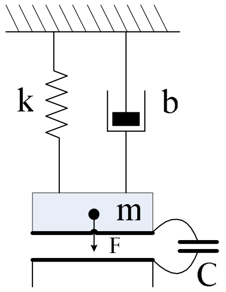

Fig.2. Reduced scheme of capacitive type accelerometer

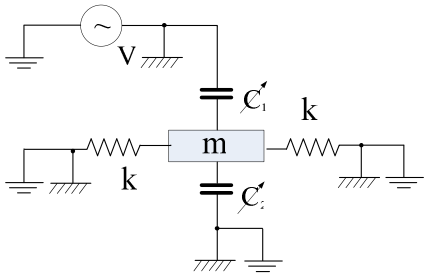

Fig.3. Reduced model of electrostatic resonator

In mathematical view presented model is represented with the help of the next differential equation systems:

$$F_{e,x} = m_x \ddot{X} + B_x \dot{X} + k_x X, \quad F_{e,y} = m_y \ddot{X} + B_y \dot{X} + k_y X, \tag{3}$$

where $F_{e,x}$ and $F_{e,y}$ - components of electrostatic scheme, which a re generated by a resonator comb elements; m_x, m_y - effective mass; B_x, B_y - damping coefficients; k_x, k_y - stiffness coefficient.

Capacitance pressure sensor [16], accelerometers and gyroscopes [18, 19, 21-25], actuators, which use for activation of electrostatic force [17, 18, 19], electromagnetic actuator [20], and other also can be reduced to the oscillation system, presented on fig. 2.

In time of second order differential equation solving, methods of Euler, Runge-Kutta, Adams and etc are used. At the same time, already existing systems like mathcad, mathematica or other can be used for solving problems at the functional level of design.

8. Component level model design

Components and element levels models have provide output parameter with high precision, which is cased by considering of nonstationary and nonlinear processes in MEMS construction and solving equation in partial derivatives. Available program systems like Ansys or Cosmos can be used for analysis of the most possible device construction. But sometimes there is a necessity in developing of state-of-the-art program system or application for separate model realization for specific MEMS element construction. Examples of corresponded mathematical models are described in works [1, 3, 4, 6, 16-20].

9. Conclusion

In the current work analysis of the MEMS design features was performed. At the basis of that the next proposition were produced: include algorithmic aspect of MEMS design; modify design process at each of hierarchical level; use parallel and downward design; for solving system level problem; use designed alternative solutions tree, theory of colored Petri networks, and branches and borders method, what allows to increase efficiency and quality of MEMS design.

Designed AND-OR graph of alternative solution and Example of the colored Petri network for MEMS structure, which includes *n* sensors, single microprocessor and *k* actuators is presented on fig. 4-5.

References

[1] Gupta R.K., Zorian Y. Introducing in Core-Based System Design //Design & Test of Computer, Oct/Dec, 1997.

[2] Биосенсоры. // Итоги науки и техники. Сер. Биотехнология. М.: ВИНИТИ, 1990. Т. 26.

[3] Krishnamoorthy U., Solgaard O., “Self-Aligned Vertical Comb-drive Actuators for Optical Scanning Micromirrors,” 2000 IEEE/LEOS International Conference on Optical MEMS, Okinawa, Japan, Sep. 2001.

[4] Krishnamoorthy, U., Li, K.., Yu, K., Lee, D., Heritage, J.P and Solgaard, O. “Dual-Mode micromirrors for Optical Phased Array Applications”, Transducers’01, Munich, Germany, June 2001.

[5] Torsten Gerlach, Helmut Wurmus, "Working principleand performance of the dynamic micropump", Sensors and Actuators A50, 1995, pp.135-140.

[6] Тернер Э., Карубе И. Биосенсоры: основы и приложения. М.: Мир, 1992. 770 с.

[7] Fatikow, S and Rembold, U, (1997). Microsystems Technology and Microrobotics, Springer, New York.

[8] Петренко А. И., Семенков А. И. Основы построения систем автоматизированого проэктирования, - К.: Вища школа, 1984. – 296 с.

[9] Петренко А. И. Основы автоматизации проєктирования. – К.: Техніка, 1982. – 295 с.

[10] Лобур М. В., Теслюк В.М., Керницький А. Б., Денисюк П. Ю., Раєвський П. Ю. Гетерогенна система автоматизованого проектування вбудованих систем. Вісник Національного університету «Львівська політехніка» № 534 "Радіоелектроніка та телекомунікації". -Львів, 2005р., 130 - 138 с.

[11] Таха Х. Введение в исследование операций: В 2-х кн. Кн. 1. Пер. с англ. - М.: Мир, 1985. - 479 с.

[12] Таха Х. Введение в исследование операций: В 2-х кн. Кн. 2. Пер. с англ. - М.: Мир, 1985. - 496 с.

[13] Дж. Питерсон. Теория сетей Петри и моделирование систем. М. Мир, 1984.

[14] Котов В.Е. Сети Петри. М.: Наука, 1984.

[15] Лобур М.В., Теслюк В.М.,Свиридова Т.В., Денисюк П.Ю., та інші. Математическое моделирование исходных электрических и конструктивных параметров резонатора емкостного типа. Электронная техника: Межвузовский сборник научных трудов. Под. Редакцией Д.В.Андреева. Ульяновск: УлГТУ, 2004, с.89-96. ISBN 5-89146-555-8

[16] Лобур М.В., Теслюк В.М., Колесник К. К. Математична модель для аналізу вихідних характеристик інтегрального сенсора тиску на компонентному рівні проектування. Науково-технічний збірник „Электроника и связь", Тематичний випуск „Проблеми електроніки", Ч.2, Київ, НТУУ "КПИ", 2005 р. – 109-111 с.ISSN 1811-4512

[17] Vasil Teslyuk, Pavlo Denysyuk. Mathematical Model For Electrostatic Micropumps. Proceeding of the 1st International Conference of Young Scientists "PERSPECTIVE TECHNOLOGIES AND METHODS IN MEMS DESIGN" , 25 – 28 May, 2005

[18] C. Yeh and K. Najafi, "CMOS interface circuitry for a lowvoltage micromachined tunneling accelerometer," Journal of Microelectromechanical Systems, vol. 7, no. 1, pp. 6–15, 1998.

[19] C.H. Liu and T.W. Kenny et al., "Characterization of a highsensitivity micromachined tunneling accelerometer with micro-gresolution," Journal of Microelectromechanical Systems, vol. 7, no. 2, pp. 235–244, 1998.

[20] Vasil Teslyuk, Pavlo Rayeskyy, Mykhaylo Lobur, Konstantyn Kolesnyk. Mathematical Model Of The Magnetic Actuator. Proceeding of the 1st International Conference of Young Scientists "PERSPECTIVE TECHNOLOGIES AND METHODS IN MEMS DESIGN" , 25 – 28 May, 2005

[21] Geiger W., Merz J., Fischer T., Folkmer B., Sandmaier H., Lang W. The silicon angular rate sensor system DAVED // Sensors and Actuators. 2000. 84. P. 280-284.

[22] Ачильдиев В.М., Дрофа В.Н., Рублев В.М. Микромеханический вибрационный гироскоп-акселерометр // Микросистемная техника. 2001. № 5. С. 8-10.

[23] Погалов А.И„ Тимошенков В.П., Тимошенков С.П., Чаплыгин Ю.А. Разработка микрогироскопов на основе структур кремния и стекла // Микросистемная техника. 1999. № 1. С. 36-40

[24] Патент № 2039994 (РФ). Компенсационный акселерометр / В.И. Баженов, И.В. Вдовенко, В.А. Рязанов, В.М. Соловьев // БИ 1995. №20.

[25] Lestev A.M., Popova I.V. Micromechanical Gyroscopes Present State in Theory and Practice // 5-th St. Petersburg International conf. on integrated navigation systems, May 1998. P. 173-182.

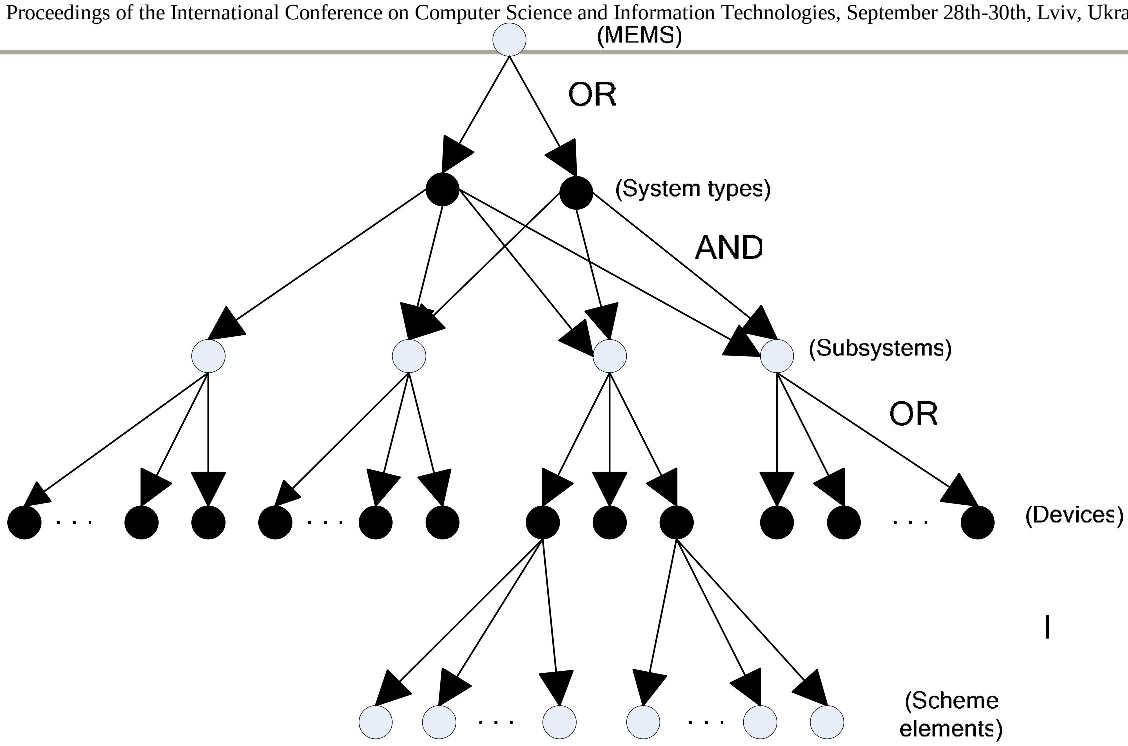

Fig.4. AND-OR alternative solutions graph

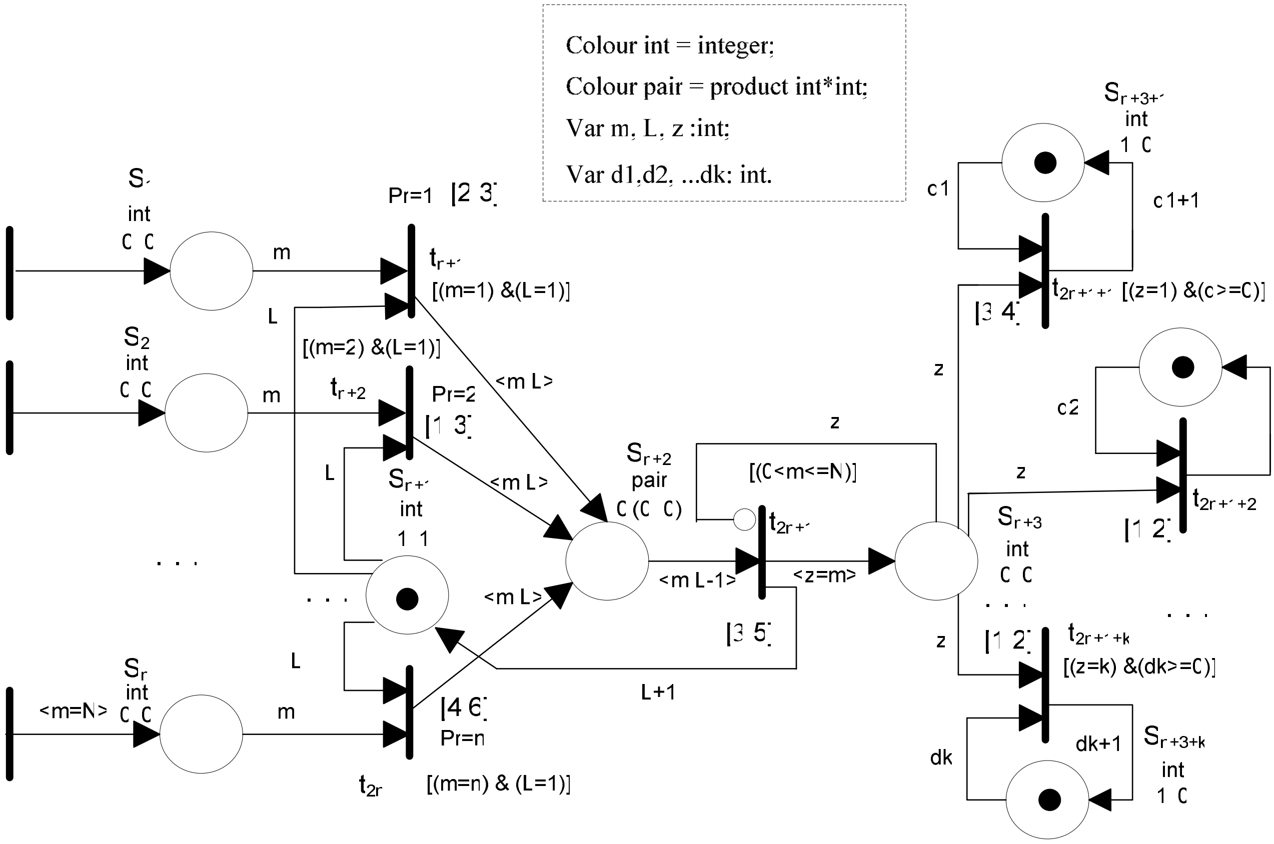

Fig.5 Example of the colored Petri network for MEMS structure, which includes *n* sensors, single microprocessor and *k* actuators.