Computational Nanomechatronics: A Pathway for Control and Manufacturing Nanorobots

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Abstract

This paper describes an innovative work for nanorobot design and manufacturing, using a computer simulation and system on chip prototyping approach. The use of CMOS as integrated circuits, with the miniaturization from micro towards nanoelectronics, and the respective advances of nanowires are considered into the proposed model design and discussed as a practical pathway to enable embedded sensors for manufacturing nanorobots. The proposed nanorobot model is applied to hydrology monitoring. It can be useful for agriculture or environmental monitoring and management.

Keywords: *Control systems, electromagnetic sensors, environmental monitoring, lithography, mechatronics, nanorobots, nanotechnology, nanotubes, NEMS, photonic.*

1. Introduction

This work presents an innovative approach to evaluate hydraulic conductivity, considering nanorobots as a new paradigm to enable more precise analysis in the field of hydrology monitoring. The application of nanorobots for agricultural purposes and monitoring water and soil qualities may result in impressive impact towards environmental control and decreasing the damages caused by pollution to many different natural species. Applications of nanorobots are expected to provide remarkable possibilities [38], [8], [6], [15], [26]. Over the past 15 years, insight was gained into the hydraulic conductivity of fractured and karstic rocks by introducing particles of different size, charge, and chemical composition into a flow field and monitoring the breakthrough of these particles in space and time. From this information, it is possible to infer the hydraulic aperture of the smallest throats in a flow path. Therefore, this concept can be extended to porous media using nanorobots [37].

A computational approach is described for the investigation of nanorobots manufacturing design [3], which aims to enable better tools for hydraulic conductivity interpretation. A total market for nanotechnology-based environmental applications in 2005 was evaluated in $374.9 million, and by 2010 this market will have reached more than $6.1 billion [1]. Advantages of using nanorobots for environmental tasks are quite clear: more control in measuring micro-organisms, better detection of pollutants, and improved control of water temperature, just to quoting some positive aspects.

The nanorobots hardware feasibility may be observed as the result of most recent advances in a broad range of manufacturing techniques. Inside the miniaturization trends, it is reasonable to even quote some examples such as VLSI chips, including here Complementary Metal Oxide Semiconductor (CMOS) based on current technology [30], which could be observed as one possible way for manufacturing embedded control computation on molecular machines in near future [4]. Meanwhile these manufacturing methodologies may advance progressively [22], [35], [16], [23], the use of computational nanomechatronics and virtual reality could help in the process of transducers investigation [18]. Thus, this work aims to outline the ways to manufacture nanorobots system on chip to prepare its use for upcoming applications which may concern agricultural, industrial and environmental issues.

2. Potential Applications

The main areas for potential environmental management could be identified with application in remediation, protection, maintenance, and enhancement [1]. Temperature and electromagnetic parameters could be successfully applied to achieve nanorobots suitable control to trigger its actuation upon predefined parameters in open workspaces. Such approach ensures feasible manufacturing perspectives and enables accurate control activation as it is described throughout the paper. Computer aided design tools is used including the main parameters required for the investigation at micro-nanoscopic levels as part of our ongoing projects, both for manufacturing as for control system design validation. The simulation includes its visualization with 3D real time analyses using the software Nanorobot Control Design (NCD) to perform a pre-defined set of tasks, based on environment sensing and trigger behaviors (figure 1).

Wireless sensors with distributed robotic agents in determined areas should be one of the most effective ways for monitoring large areas of natural resources, especially in comparison with human driven boats for 24 hours monitoring water resources under bad or severe weather conditions [34]. The use of nanotubes and nanowires has demonstrated a large range of possibilities for use to manufacture better sensors and actuators with nanoscale sizes. Those developments allied with 3D computational simulation may facilitate the manufacturing design of nanorobots with integrated embedded nanoelectronics and circuits [18].

3. Nanorobot Manufacturing Design

The approach taken in our development is called Nanobhis (Nano-Build Hardware Integrated System). It represents a joint set of well established techniques and new methodologies from nanotechnology with the aim of manufacturing nanorobots. The nanorobot must be equipped with the necessary devices for monitoring the most important aspects of its operational workspace. Depending on the case the temperature, concentration of chemicals in the water, and electrical conductivity, are some of relevant parameters when monitoring hydrological resources. Geographically distributed teams of nanorobots are expected to open new possibilities on agricultural and environmental applications with a larger spectrum of details not seen whenever. For such aims, computing processing, energy supply, and data transmission capabilities can be addressed through embedded integrated circuits, using advances on technologies derived from VLSI design [30]. CMOS VLSI design using deep ultraviolet

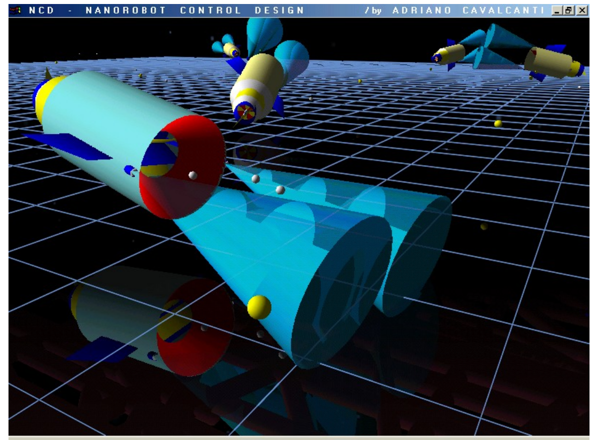

Fig. 1: Schematic view of nanorobot's sensor identification.

lithography provides high precision and a commercial massively way for manufacturing nanodevices and nanoelectronics. The CMOS industry may thrive successfully the pathway to enable nanorobots assembly, where the jointly use of nanophotonic and nanotubes may even accelerate further the actual levels of resolution ranging from 248nm to 157nm devices [2]. To validate designs and to achieve a successful implementation, the use of VHDL has become the most common methodology utilized in the industry of integrated circuits.

3.1. Temperature Sensor

Integrated nanothermoelectric sensors could be implemented as CMOS devices with promising uses in hydrology [37]. Such approach may permit a large production of infrared thermal sensors applied into different ranges of wavelength with interesting possibilities for environmental monitoring. This same approach could be tailored for other application areas such as industrial manufacturing process or even medicine [21]. CMOS as a thermoelectric sensor has advantage of linear self-generated response with system integration without requiring bias or temperature stabilization [29]. Thus the infrared array could be integrated on a single chip within amplifiers and signal processing capabilities. Such approach allows a fast pace towards miniaturization with no loss of efficiency due electromagnetic noise [21], [27]. CMOS could be operated at very low voltage levels, which is also a positive aspect, presenting good functionality and requiring little energy. Cantilever and bridge types are also valid techniques for possible different ways to implement CMOS thermoelectric sensors.

Nanowires are suitable for fabricating CMOS based on integrated nanodevices [7]. Carbon nanotubes are able to improve performance with low power consumption for nanosensors. Its particular high precision make it quite useful for applications in infrared supersensitive sensors, with applications such as water temperature measurements, detection of body temperature changes, sense of human touch, as well as industrial flow-shop control. Nanosensors present important electrical properties, high thermal conductance and fast frequency response [11]. The power consumption with NEMS is three times lower if compared with traditional MEMS thermal sensors, where for MEMS the operating values range in terms of mW [29]. Nanowires can be configured as two-terminal devices electrically designed to work as high or low resistance diodes. Crossed nanowire p-n junctions can function successfully as logic gates from crossed nanowire field-effect transistors [7]. Therefore, microwire pitch incorporated in actual CMOS integrated designs can be reduced to the nanowire pitch by using on-off masks aligned diagonally to produce a one-to-one microwire to nanowire correspondence [7].

3.2. Mineral Detection

The application possibilities for sensors to identification of distinct metals are huge. Just as an example, nowadays the number of classified mines in the world is around 100 million [24]. Electromagnetic sensors could also be applied to a variety of cases: analyses of massively circuit board production, industrial evaluation of magnetic material properties, naval operation, and medical diagnosis or even control quality for some products in the food industry [20]. Such sensors have been widely applied also to classify small or large pieces of rocks and related materials. Electromagnetic induction sensors are the most suitable way for metal and low-metal content detection [27]. It serves to detect fragments of metals from different depths and different environment conditions, with distances varying in accordance to the object size and characteristics.

In comparison with passive sensors, active electromagnetic sensors can enable a broader range of identification patterns [27]. They should be easily applied to classifying ferromagnetic as well as nonmagnetic metallic objects, and in some circumstances even for non-metallic objects [27]. It works with the use of electromagnetic pulse given a signal proportional to the rate of change of magnetic resonance, which is influenced by the orientation tolerance and angular dependence on the incident beam above the target to identify. The signal received back by the sensor will reflect the distance, shape, electrical conductivity, and magnetic permeability, and those aspects should be considered for spectral recognition [27]. Considerations on energy concerns of sensors on a nanochip make the use of electromagnetic resonance useful for short distance identification. To module the electromagnetic sensor operation to fit different kinds of targets a multifrequency calibration is necessary.

To achieve a higher performance on electromagnetic sensor use of photonic technology are also expected to play an important rule on manufacturing CMOS sensor devices [33]. It extremely increases the sensor functionality and precision permitting better alignment of subcomponents. Due to photonics intrinsic properties, this is achieved using lithography for chip implementation without to require expensive active methods. High precision nanoelectronics can be therefore manufactured using photonic properties using e-beam lithography with wavelengths down to 300 nm [9]. Nanophotonic SOI UV lithography could be used for fabrication of high performance CMOS sensors, which permits precision on assembly process range 1 to 10nm scales [2]. Photonics wires are more appropriated for such process because they are not periodic having lower dispersion.

3.3. Energy Supply

The most effective way to keep the nanorobot operating continuously is to establish the use of power generated from the available sources in the environment where it must be working. Some possibilities to power it can be provided from ambient energy. Kinetic energy can be generated from water stream due motion interaction with designed devices embedded outside the nanorobot [28]. Electromagnetic radiation from light could be another option for energy generation in open workspaces [17]. Temperature displacements could likewise generate radiation developing pre-established voltages. Cold and hot fields from in series connected conductors may also be useful to produce energy using the well-established Seebeck effect [11]. Temperature changes or light variations for different kinds of workspace could sharply variates depending on the application. Considering a broader design choice, the energy generated by kinetic vibration is more appropriated. It is more suitable for a larger variety of applications for environmental monitoring or even biomedical problems.

A device for power generation using integrated circuits allied with Li-ion batteries is a good choice to provide electrical sources for the nanorobot operation. Thus energy generated is saved in ranges of ~1μW while the nanorobot can stay in inactive modus, just becoming active when signal patterns requires so. Some of the typical tasks may require the nanorobot to spend low power amounts, once strategically activated. For communication sending RF signals ~1mW is required. A system with resonance frequency as μPG (micro power generator) is suitable for power supply [19]. Outside liquid vibrations once captured is translated with piezoelectricity, into energy source for the nanorobot operation. Due operational aspects such as integration and power density [28], it is a more efficient approach than electrostatic or electromagnetic induction [33]. Allied with the power source devices, the nanorobots need to perform strategically defined actions in the workspace, in order to save energy using such resource wisely. Therefore the team of nanorobots can be prepared to acquire and transmit more or less information depending on changes in determined area. The collected data can be expressed in bits pattern signals, what permits to keep the power consumption with data transmission low.

3.4. Data Transmission

The application of sensor to transmit data on monitoring environmental and agricultural resources has shown yet great benefits. For communication in liquid workspaces, depending on the aim in mind and range of distances, it is worth to quote acoustic, light, RF, and chemical signals as possible choices for communication and data transmission [32], [34], [4]. Chemical communication is quite useful for nearby communication among nanorobots for some teamwork coordination [10]. Acoustic communication by other hand is more appropriated for long distance communication and detection with low energy consumption if compared to light communication approaches [4], [12]. Although optical communication permits faster rates of data transmission [34], its energy demand makes it not ideal for nanorobots.

RFID sensors have been used to identify and inventory livestock, and possibly to control the spread of disease [32]. A tiny RFID integrated circuit was applied by environmentalists and fishing industry, both to better analyze the decreasing of salmon population in recent years with its possible relationship to global warming and environment changes, as well as an automatic system to catch salmon more efficiently [31]. The gas and oil industry operational procedures may also directly benefit with the use of nanorobots integrated sensors systems. It can act as mobile devices to monitor large areas for underwater or hazardous conditions [5]. Prevision of low cost polymer electronics for tiny magnetic sensors and transducers chips are expected to achieve low costs as 1 cent for circuit, what makes its use even more attractive [36].

Using integrated sensors for data transfer is the better answer to read and write data in underwater workspaces. Electromagnetic fields combined with passive sonar signature techniques should be the best approach for data transmission to monitoring underwater surrounding environments [27]. The teams of nanorobots should be equipped with CMOS sensors [25]. CMOS with submicron SoC design could be used for extremely low power consumption with nanorobots communicating through sonar sensors [14]. For the nanorobot active sonar communication frequencies may reaches up to 20μW@8Hz as resonance rates and 3V supply [12]. Mixing static and mobile sensors for data transmission is a quite useful and widely accepted approach for monitoring environmental and hydrological resources [34]. Thus, strategically positioned static sensors for acquiring wireless data transmission from mobile nanorobots comprise a good choice to patrol and monitoring predefined patterns from some target area. To accomplish that, acoustic micron sensors may be exchanging communication and strategic data information should be transmitted when some new event was registered from nanorobots as mobile sensor in the specified region.

In our design an electromagnetic reader is applied to launch waves and detect the current status of nanorobots in the spread area. This transponder device emits magnetic signature to the passive CMOS sensors embedded in the nanorobot, which enable sending and receiving data through electromagnetic fields. The nanorobots monitoring data convert the wave propagation generated by the emitting devices through a well defined protocol. According with a last set of event recorded in pattern arrays, information can be reflected back by wave resonance [36]. For nanorobot passive data transferring ~4.5 kHz frequency with approximate 22 μs delays are possible ranges for data communication. While for capturing data from the nanorobots should be achieved with such passive process, sonar communication is to be used for active communication among nanorobots to perform coordinated behaviors due some specific collective tasks to be fulfilled.

3.5. System on Chip

Advances on nanotechnology may enable manufacturing nanosensors and actuator in short time. Indeed it is happening actually with the implementation of nanotransistor and integrated circuits. Possible breakthroughs for it are hybrid approaches using nanotubes, photonics and mesoscopic nanowires as elements for design. For hydrology monitoring there is not a so strict parameter size limitation, thus a photolithographic pattering of the insulator layer underneath the MEMS bridge was used for prototyping a CMOS as a first attempt towards future assembly of nanoscopic parts.

The integration and manufacturing process for the circuit switch is shown at figure 2. Followed by deposition of 1500 Å silicon nitride and acetone lift off, where a deposition of 1.5 μm sacrificial layer of AZ5214E photoresist is used to define g_0 gap dimension [13]. Then, the pattering of the windows related to the bridge columns is made. A hard bake is needed to avoid damages to the photoresist caused by the gold bath solution during the electro formation of

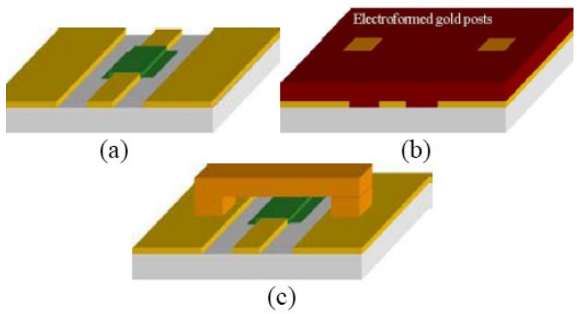

Fig. 2: Process sequence overview. (a) Si3N4 DC isolation; (b) Gold posts electrolytic growth, and (c) circuit switch.

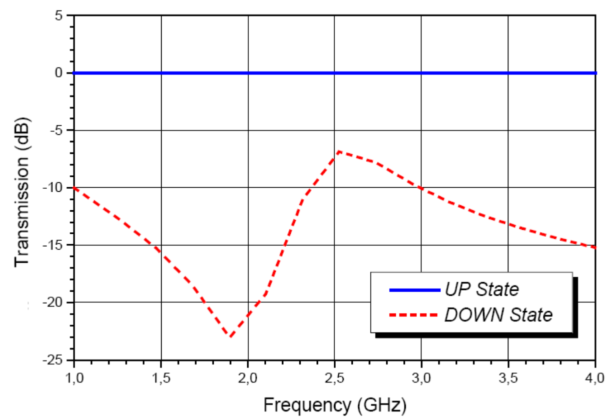

Fig. 3: Transmission characteristics for circuit switch - UP and DOWN States.

the structures [13]. Electro formation of 1.5 µm gold posts is included. In the CMOS built sensor was included the isolation layer with silicon nitride layer [13]. Two states of the MEMS switch were simulated: in the UP State the CPW line transmits the wave normally, as can be observed by the transmission curve in figure 3. In the DOWN state the transmission line is short-circuited, with isolations lower than -7 dB in the worst case, as can be seen by the transmission curve (dashed line) in the same figure. Another parameter that may be analyzed during the simulation steps is the input return loss. For this proposed switch, in the UP state, it is lower than -35 dB at the operation frequency band.

This manufacturing process CMOS has been adopted as a first study case, where further experiments can lead us to down scaling sizes with more precise specification on using nanotubes, and photonics advanced materials to achieve high precision and performance integrated circuits. As discussed throughout the paper, to achieve a complete nanorobot assembly based on dynamic capability behavior, different sensors should be accomplished both in design simulation, as well as in manufacturing implementation. The recent achievements on VLSI and lithography allied with precision verification tools such as SoC and VHDL are enabling remarkable breakthroughs on electronic advances.

4. Conclusions

The use of well established techniques such as SoC and Lithography, VHDL and 3D Simulation, allied with nanotechnology advances, such as mesoscopic nanowires, nanophotonics, and nanotubes, may contribute together as a pathway to validate and implementation of high complex VLSI featuring functionality and exceptional performance under nanoscale sizes. The development of nanorobots applied to environmental issues should also help providing information useful for manufacturing tailored thinner nanorobots for biomedical applications. The perspectives that the same manufacturing technologies required to assembly nanorobots could be applied to a very broad range of fields, turns the investigation of new methodologies to achieve such accomplishment as fast as possible on assembly nanodevices and nanoelectronics to build nanorobots very promising.

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