# Computational Nanorobotics: Agricultural and Environmental Perspectives


Adriano Cavalcanti[1,4] Warren W. Wood[2] Luiz C. Kretly[3] Bijan Shirinzadeh[1]

[1]*Robotics and Mechatronics Research Lab., Dept. of Mechanical Eng., Monash University*
Clayton, VIC 3800, Australia
emails: bijan.shirinzadeh@eng.monash.edu

[2]*Department of Integrative Studies, Michigan State University*
East Lansing, MI 48824, USA
email: wwwood@msu.edu

[3]*Microwave and Optics Dept., Electrical and Computer Engineering School, State University of Campinas*
Campinas, SP 13083, Brazil
email: kretly@dmo.fee.unicamp.br

[4]*CAN Center for Automation in Nanobiotech*
Sao Paulo, SP 01540, Brazil
email: adrianocavalcanti@canbiotechnems.com



*Abstract*—**Recent developments in molecular fabrication, computation, sensors and motors will enable the manufacturing of nanorobots. The present work contributes with such aim, describing a platform suitable for the design and manufacturing research, using computer simulation and system on chip for prototyping. 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 suitable path-way to enable embedded sensors for manufacturing nanorobots. The proposed nanorobot model is applied to hydrology monitoring with aims focused on economical aspect related to agriculture or production based on natural resource activities. Moreover, the use of nanorobots in enviromental monitoring is also presented. Teams of nanorobots could be used to patrol a hydrological predefined area.**



*Index Terms*—**Agricultural management, control systems, electromagnetic sensors, environmental monitoring, hydrology, lithography, manufacturing, mechatronics, mesoscopic nanowires, nanorobots, nanotechnology, nanotubes, NEMS, photonics, SoC, transducers, VHDL, VLSI, virtual reality.**


## 1. INTRODUCTION

This paper presents an innovative approach to evaluate hydraulic conductivity, considering nanorobots as a paradigm capable to open new perspectives 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. Recent developments in the field of biomolecular computing [2], [53], [10] have demonstrated the feasibility of processing logic tasks by bio-computers [17], which is a promising first step to enable future nanoprocessors with increased complexity. Studies targeted at building biosensors [40], [7] and nano-kinetic devices [39], required to enable nanorobotics operation and locomotion, have been advancing recently as well.

Over the past 15 years, we have gained insight 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, we may infer the hydraulic aperture of the smallest throats in a flow path. Therefore we may be able to extend this concept to porous media using nanorobots [49]. We describe a computational approach for the investigation of nanorobots manufacturing design [8] to enable better tools for hydraulic conductivity interpretation. The nanorobots are using chemical gradients and electromagnetic sensing over short distances along specific flow paths to solute integrated estimates of hydraulic conductivity. Such information acquisition process is quite useful to define geological characteristics, which are at most important when agricultural management or environmental disasters arises requiring efficient decisions in short time, or even more to improve productivity in some industrial activities as described through the paper. 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 [5]. Geophysicists have held out hope of ways to describe hydraulic conductivity distribution with new analytical and detection methods and yet, we are little closer to the illumination of this Holy Grail than we were 40 years ago. The limitation of geophysical methods falls into two categories. First, there is a limitation of direct measurement on the size of the features we are looking for (pore throats). These small features require a short wavelength and thus high energy for resolution. Unfortunately, energy is rapidly dissipated in travel through earth material, generally resulting in degraded resolution at the desired scales. This wavelength/energy constraint is fundamental and cannot be overcome. Second, because geophysicists are unable to directly measure the feature of interest, they measure a surrogate of pore-throat sizes. That is, typical geophysical methods measure properties of waves, density, or electrical conductivity, which is used to generate lithologic information.


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The ways to achieve electromagnetic sensing devices embedded into the nanorobot are described in our paper. Data from these sensors, when combined with a nano-positioning system for four-dimensional reference location, could either be stored in memory that could be downloaded after capture of the nanobots at some distance along the flowfield or be accessed by a signal from the surface, defining this way preferential flow paths. Such approach could be used even for tracking distinct materials - oil, uranium, or gold, just to quote a few. 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, we may even quote some examples such as VLSI chips, including here Complementary Metal Oxide Semiconductor (CMOS) based on currently technology[10], which could be observed as one possible way for manufacturing embedded control computation on molecular machines in near future [9]. Meanwhile these manufacturing methodologies may advance progressively, the use of computational techniques and virtual reality could help in the process of transducers investigation [27]. 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. Environment Monitoring

The main areas for potential environmental management could be identified with application in remediation, protection, maintenance, and enhancement [5]. Developments on SoC (System on Chip) could enable hardware manufacturing in the upcoming few year using CMOS and other related technologies. Chemical, electromagnetic and thermal 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 we discuss throughout the paper. We use computer aided design tools 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 included 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).

The planet Earth superficies majority is covered by water, and the hydrologic cycle has impressive importance and direct impact with clear consequences in the whole mankind and all the life systems around the world. Only the ocean represents 70% of the superficies around the world. The good or bad management of hydrologic resource now may signify dramatic and devastating impacts for the agricultural production in the coming few years. 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 [45].

Advantages of using nanorobots for environmental tasks are quite clear: more control in measuring micro-organisms, better

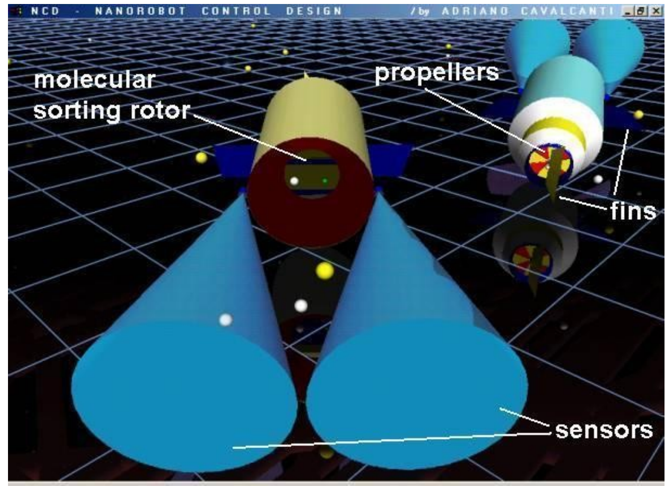


Fig. 1: Nanorobot 3D design - the depicted blue cones shows the sensors "touching" areas.

detection of chemical pollutants, and improved control of water temperature, just to quoting some positive aspects. The system could be used to save many lives against catastrophic storms or natural disaster due a more precise monitoring of surround changes in the environment. Tremendous benefits may be expected from nanotechnology and the miniaturization of electronics. 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 [27]. In comparison to biomedical nanorobots, the use of nanorobots for environment monitoring could be easier assembled through the implementation of a first series of nanomachines comprised of harmonically integrated Nanoelectromechanical systems (NEMS) and Microelectromechanical Systems (MEMS) devices. It may be possible due the fact that for hydrological monitoring the sizes of nanorobots aren't so strict as for the case of biomedical issues, where the sizes of nanorobot could not surpass 3 microns in diameters in the majority of cases. Medicine may also benefit of such developments of nanorobots in environmental issues, mainly because investigation on manufacturing, control and operation of nanorobots in natural environments should accelerate at the same time the first nanorobots tailored for biomedical applications.

## 3. Nanorobot Sensors

The nanorobot proposed prototyping 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 [38].

CMOS VLSI design using deep ultraviolet 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 [6]. 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 [35].

## 3.1 Pollutant and Chemical Detection

Manufacturing silicon and chemical based sensor arrays using two-level system architecture hierarchy have been successfully conducted in the last 15 years [3], [28]. Application ranges from automotive and chemical industry with detection of air to water element pattern recognition through embedded software programming. Through the use of nanowire significant costs of energy demand for data transferring and circuit operation can decrease around 60% [50]. CMOS sensors using nanowires as material for circuit assembly can achieve maximal efficiency for applications regarding chemical changes, both in environmental care and biomedical applications. Due resistivity characteristics, nanocrystallites and mesoscopic nanowires performance is impressive if compared with larger sensors enabled technologies [14], [46], [26], [52].

Sensors with suspended arrays of nanowires assembled into silicon circuits can drastically decrease self-heating and thermal coupling for CMOS functionality [16]. Nanometer chemical sensors using integrated circuits may generate huge profits with low cost for massively production of commercially devices with a wide range of applications in medical, industrial, environmental issues, and much more. Factors like low energy consumption and high-sensitivity are among some of advantages of nanosensors. Nanosensor manufacturing array process can uses electrofluidic alignment to achieve integrated CMOS circuit assembly as multi-element [50]. Passive and buried electrodes should be used to enable cross-section drive transistors for signal processing circuitry readout. The passive and buried aligned electrodes must be electrically isolated to avoid loss of processed signals.

Control feedback to switch the electronic sensor between active or turned off sensing are quite appropried for monitoring operations. The use of nanowire for integrated sensors is to achieve new breakthroughs in high speed sensing and control technologies. For chemical sensor device the range for the CMOS operation is ~190MHz. Control of data transmission is the most suitable path for save the nanorobot's energy when the sensor is in operation, thus sample techniques can be used with time interval of 80 ns for active circunstances [50].

Some of limitations to improve actual CMOS and MOSFET methodologies are quantum-mechanical tunneling for operation of thin oxide gates, and subthreshold slope [48]. Surpassing any expectations the semiconductor branch has moved forward to keep circuit advancing. Smaller channel length and lower voltage circuitry for higher performance are being achieve with new materials aimed to attend the growing demand of high complex VLSIs. New materials such as strained channel with relaxed SiGe layer are quoted to beat self-heating and improve performance [4]. Recent developments on 3D circuits and FinFETs double-gates has achieved astonishing results and according to the semiconductor roadmap should improve even more. To advance further manufacturing techniques, Silicon-On-Insulator (SOI) technology has been used for assembly high-performance logic sub 90nm circuits [29], [44]. Circuit design approaches to solve problems with bipolar effect and hysteretic variations based on SOI structures has been demonstrated successfully [4]. Altogether, it is turnning feasible 90nm and 65nm CMOS devices as an actual breakthrough in terms of technology devices into products that can be utilized strategically.

## 3.2 Metal Identification

The application possibilities for sensors to identification of distinct metals are huge. Electromagnetic sensors could 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 [30], [31]. 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 [33]. 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. Nowadays the number of classified mines in the world is around 100 million [34].

In comparison with passive sensors, active electromagnetic sensors can enable a broader range of identification patterns [37]. They should be easily applied to classifying ferromagnetic as well as nonmagnetic metallic objects, and in some circunstances even for non-metallic objects [37]. 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 [37]. Considerations on energy concerns of sensors on a nanochip make the use of electromagnetic resonance useful for short distance identification. This may be successfully performed by teams of nanorobots with integrated CMOS technology, which could in a unprecedented fashion be used to short range sensing coordination. 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 expeted to play an important rule on manufacturing CMOS sensor devices [43], [25]. It extremely increases the sensor functionality and precision permiting better alignment of subcomponents. Due to photonics intrinsic properties, this is achieved using lithography for chip implementation without to require expensive active methods [1]. High precision nanoelectronics can be therefore manufactured using photonic properties using e-beam lithography with wavelengths down to 300 nm [12], [13]. 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 [51], [20]. Photonics wires are more appropriated for such process because they are not periodic having lower dispersion [6].

### 3.3 Nanorobot Data Transmission

The application of sensor to transmit data on monitoring environmental and agricultural resources has shown yet great benefits. RFID sensors have been used to identify and inventory livestock, and possibly to control the spread of disease [42]. 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 enviroment changes, as well as an automatic system to catch salmon more efficiently [41]. When dealing with underwater environments the use of automatic robotics could bring significantly improvement in terms of 24 hours monitoring with higher precision and lower costs. In such scenery nanorobots are expected to enable great impact on data collecting. Not only hydrological search and analytical environmental conclusion reports, but also the gas and oil industry operational procedures may directly benefit with the use of nanorobots integrated sensors systems. It can act as mobile devices to monitor large areas for underwater or hardazous conditions. Thus securance and mantaince operations could become more secure, automatic, and with lower costs, through the use of smart sensors to help identify what repair should become urgently necessary on underwater pipelines and pumping equipments [11]. 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 [47].

Eletromagnetic fields combined with passive sonar signature techniques should be the best approach for data acquision for monitoring underwater surrounding environments [37], [24], [15], [19]. The teams of nanorobots should be equiped with CMOS sensors [22], [36]. CMOS with submicron SoC design could be used for extremely low power consumption with nanorobots communicating through sonar sensors [32], [23]. For the nanorobot active sonar communication frequencies may reaches up to 20µW@8Hz as ressonance rates and 3V supply [18]. Mixing static and mobile sensors for data transmission is a quite useful and widely accepted approach for monitoring environmental and hidrological resources [45]. 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 transmited when some new event was registered from nanorobots as mobile sensor in the specified region.

For communciation in liquid workspaces, depending on the aim in mind and range of distances, we may quote acoustic, light and chemical signals as possible choices for

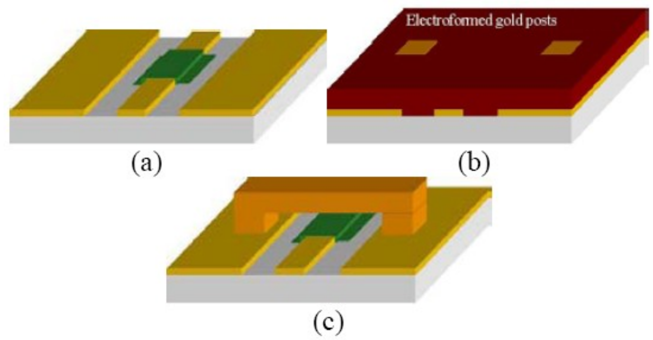


Fig. 2: Process sequence overview. (a) Si3N4 DC isolation; (b) Gold posts electrolytic growth, and (c) circuit switch.

communication and data transmission [45], [9], [7]. Chemical communication is quite usefull for nearby communication among nanorobots for some teamwork coordination [7]. Acoustic communication by other hand is more appropriated for long distance communication and detection with low energy consumption if compared to light communication approaches [9], [18]. Although optical communication permits faster rates of data transmission [45], its energy demand makes it not ideal for nanorobots.

Using integrated sensors for data transfer is the better answer to read and write data in underwater workspaces. 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 receing data through electromagnetic fields. The nanorobots monitoring data convert the wave propagation generated by the emiting devices through a well defined protocol. According with a last set of event recorded in pattern arrays, information can be reflected back by waves ressonance [47]. 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 achived with such passive process, sonar communcation is to be used for active communication among nanorobots to perform coordinated behaviors due some specific collective tasks to be fulfilled.

## 4. Nanorobot 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 we have 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 torwards 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 [21]. 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 the structures [21]. Electro formation of 1.5 μm gold posts are included. In the CMOS built sensor was included the isolation layer with silicon nitride layer [21]. 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 dow 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 achievement VLSI and lithography allied with precision verification tools such as SoC and VHDL are enabling remarkable breakthroughs on electronic advances.

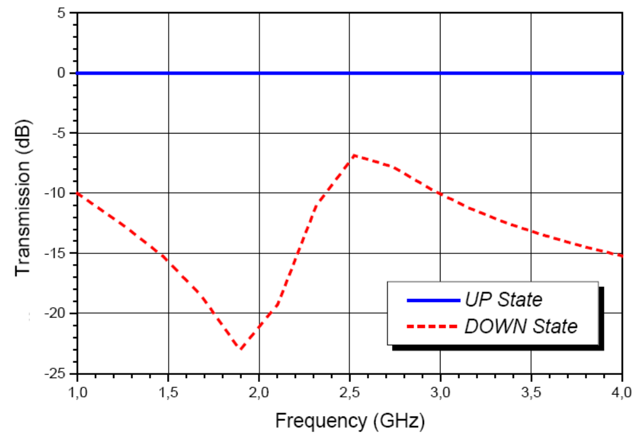


Fig. 3: Transmission characteristics for circuit switch - UP and DOWN States.

## 5. Conclusions

The application of nanorobots with embedded sensor devices for hydrology is an interesting approach which may bring significant improvements for agriculture and environment monitoring in coming few years. A nanorobot device using CMOS for sensing and communication as the result of many breakthroughs in nanotechnology are expected to turn feasible the manufacturing of molecular machines as a complete integrated set of nanoeletronics. The use of yet well established techniques such as SoC and Lithography, VHDL and 3D Simulation, allied with recent nanotechnology advances, such as mesoscopic nanowires, nanophotonics, and nanotubes, may contribute together as a path-way to validate and implementation of high complex VLSI featuring functionality and exceptional performance under nanoscale sizes.

The perspectives that the same manufacturing technologies required to assembly nanorobots could be also 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 nanoeletronics to build nanorobots very exciting. The development of a first series of nanorobots for agricultural and environmental applications may help us also to understand better the world where we live. Such comprehension may enable a better management of natural resources to avoid future disasters, but more interesting on it is the fact that in the moment of effective decisions begin to take effect in efficient time, the chances of decreasing natural catastrophes improve significantly.

From the same development on build nanorobots could also benefit industrial process and industrial maintenance likewise, with more effective and more secure operations, which may also help in saving human lives. In this aspect of saving lives, with the development of nanorobot applied to environment, it should serve providing insightful information useful for manufacturing tailored thinner nanorobots for biomedical applications. The detailed framework we presented thus, describing clearly electromagnetic and chemical sensors based on CMOS technologies, may enable an insightful preview of upcoming feasible directions to practical implementation of nanorobots. We hope it may serve as a useful manufacturing approach to accomplish nanorobots for a large spectrum of applications.

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