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NANOROBOTS FOR MICROFACTORIES TO OPERATIONS IN THE HUMAN BODY AND ROBOTS PROPELLED BY BACTERIA

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Sylvain Martel

NanoRobotics Laboratory, Dept. of Computer and Software Engineering,
Institute of Biomedical Engineering, École Polytechnique de Montréal (EPM) -
University of Montréal, Montréal, Canada
e-mail: sylvain.martel @polymtl.ca

Abstract. *The exploitation of the properties at the nanoscale enables novel nanorobotic-based instrumented platforms and techniques. Here, some unique interdisciplinary examples from our research laboratory are briefly described providing some insights about the possibilities and the huge potentials of nanorobotics with main areas of applications in medicine and bioengineering, including supporting new robotic platforms for micro- and nano-manufacturing and high-throughput automatic operations at the nanoscale. For several applications where specifications cannot be met using modern technologies, especially at such small scales, a highly interdisciplinary approach integrating biological components in engineered systems becomes an essential part of the development process.*

Key words: *Nanometer-scale operations, blood vessels, magnetic resonance, flagellated bacteria, magnetotaxis*

1. INTRODUCTION

Interest in science and engineering at the nanometer scales is growing at a fast pace since it promises to revolutionize many fields of research. This is due in great part to the fact that a number of physical properties changes when compared to macroscopic systems.

Similarly, nanorobotics is a field of robotics that depends on these nanoscale properties. As such, nanorobotics is not just about robots with overall dimensions at the nanometer scales.

Indeed, in a more practical approach due to technological constraints, the field of nanorobotics includes microscale or larger robots relying on embedded nanoscale components; and much larger robots capable to operate at the nanometer scales.

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Hence, nanorobotics can be more than just scientific curiosities but when designed appropriately, nanorobots can also play an important role in the development of new instrumented platforms. To provide an overview of the potential and the role that nanorobotics can play in the field of instrumentation, some examples of novel nanorobotic instrumented platforms under development in our research laboratory are briefly described.

2. EXAMPLES OF NANOROBOTIC INSTRUMENTED PLATFORMS

Instrumented platforms based on nanorobotics can take various forms depending upon the applications. Not only the applications, but the environment where the operations must take place influences the design and architecture of the platforms. The following systems being developed by our group provide a list of examples of the main architectures of nanorobotics platforms.

2.1. Platforms for the fabrication of 3D micro- and nano-structures

One of the most commonly known nanorobotic platform architectures relies on x-y-z robotic stages with precision allowing interactions at the nanometer scales. Interactions are often done using a Scanning Probe Microscope (SPM) tip. One popular application of this type of nanorobotic platforms is the manipulation of nanoscale objects for nano-assembly tasks.

Our group is investigating several platforms for the fabrication of 3D micro- and nano-structures. In our particular case, the fabrication of nanostructures relies mainly on nanofibers. These nanofibers are constructed by pulling in a well controlled manner, polymers using a SPM tip. The nanometer-level precision achieved by this platform is paid by a slower fabrication rate.

Another platform being developed allows for the fabrication and integration of microchannels using direct-writing techniques. The direct-writing technique is adapted to enable the complete conception and fabrication of complex 3D micropipe structures in the order of a few minutes using a special multi-axis motion platform. The method consists of the extrusion of a fugitive organic ink through a micro-nozzle operating under constant pressure. When combined to a layer-by-layer robotic deposition on a substrate, geometrically complex structures are created as depicted in Fig. 1 where a 3D micro-heat-pipe structure used for local heat dissipation has been deposited directly on a computer chip based on laser scan surface data acquired from the same platform.

Although deposition speeds depend on the structural pattern, nozzle diameter and ink viscosity, 3D structures can presently be built at speeds reaching ~100mm/s while maintaining a precision of ~100μm during the deposition process on intense curvature paths. To achieve such results while maintaining the same channel diameter, wall smoothness and quality over the entire structure, the velocity vector among all axes is maintained constant based upon geometrical modeling algorithms.

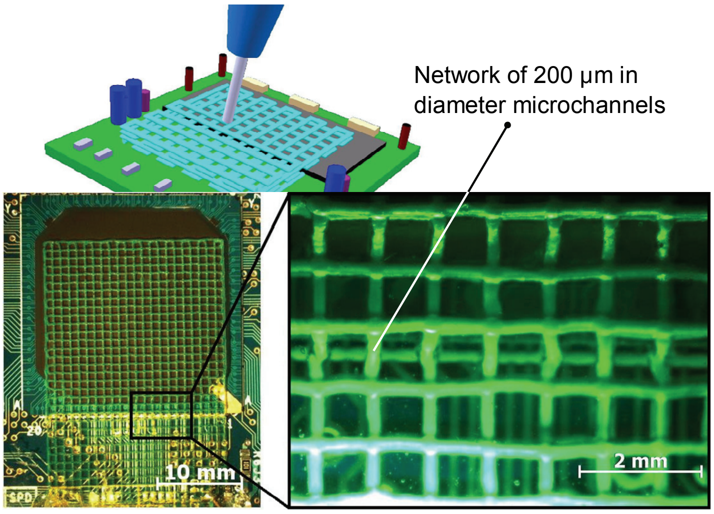

Fig. 1 Platform for the fabrication of microchannels

These often complex three-dimensional microfluidic or micro-heat-pipe structures are obtained by first, embedding the whole structures in an epoxy and second, by dissolving the deposited polymer.

2.2. Nanorobotic platforms based on a fleet of miniature instrumented robots capable of interacting at the nanometer-scales

Another type of nanorobotic system [1] being developed by our group relies on a platform based on a fleet of scientific instruments configured as autonomous miniature robots (see Fig. 2). Each untethered robot has an embedded SPM tip allowing interactions at the molecular scales. Displacement is typically achieved at approximately 4000 steps/s using three piezo-legs embedded in each robot and mounted in a pyramidal fashion with the apex pointing upward [2] allowing faster displacements. Another prototype named WalkingDie relying on wheels for displacement is also shown on the top of a US quarter (bottom right corner in Fig. 2) with a photograph of a part of the MEMS-based rotating actuator used for locomotion (top left corner in Fig. 2).

The objective of such platforms is high-throughput operations at the nanometer scales on many samples. As such, the tasks are transmitted to a central computer by the user through a special Graphical User Interface (GUI). Then, the central computer coordinates the fleet of instrumented robots and assigns tasks through wireless communication links, based on the location (distance to the next target working location) of the robot, its availability, and the type of instrument being carried.

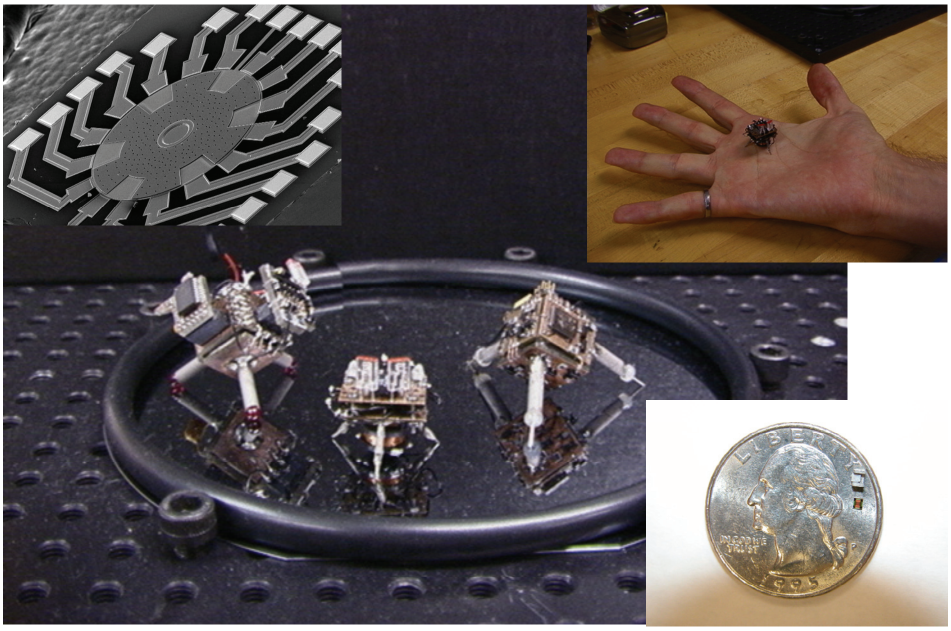

Fig. 2 Some examples of prototypes of the miniature robots designed to embed an instrument allowing autonomous operations at the molecular scale

To maximize the number of operations being performed at the molecular scales by the platform in a given time interval, not only proper scheduling but since travel distance must be minimized while increasing the number of robots, a higher density of instrumented robots through miniaturization and relatively fast displacement speeds become key issues. Due to limit in wireless communication bandwidth, computing is embedded onto each robot. Because of space constraints, power is delivered to each robot through the three legs when in contact with the floor.

There are different versions of such platforms, the first being named NanoWalker. A more recent version under development and named NanoWalker-2 uses a vertical oscillating platform (unlike the first version) to achieve further miniaturization of the robots. As the overall size of the robot decreases, the force generated from the embedded piezo-actuators or legs becomes insufficient to counteract gravitational force. Therefore, providing a null resultant gravitational force at a specific instant during each oscillating cycle and by synchronizing small directional forces from the piezo-legs, displacements can occur. An inertial micro-switch embedded in each robot creates an interrupt to an onboard processor to synchronize the activation of the legs with the movement of the floor.

2.3. Nanorobotic platforms for operations in the human body

These platforms are based on our previous development of fundamental techniques and methods for the propulsion and navigation of ferromagnetic entities in the blood circulatory network through the induction of force from magnetic gradients generated by a clinical Magnetic Resonance Imaging (MRI) system [3].

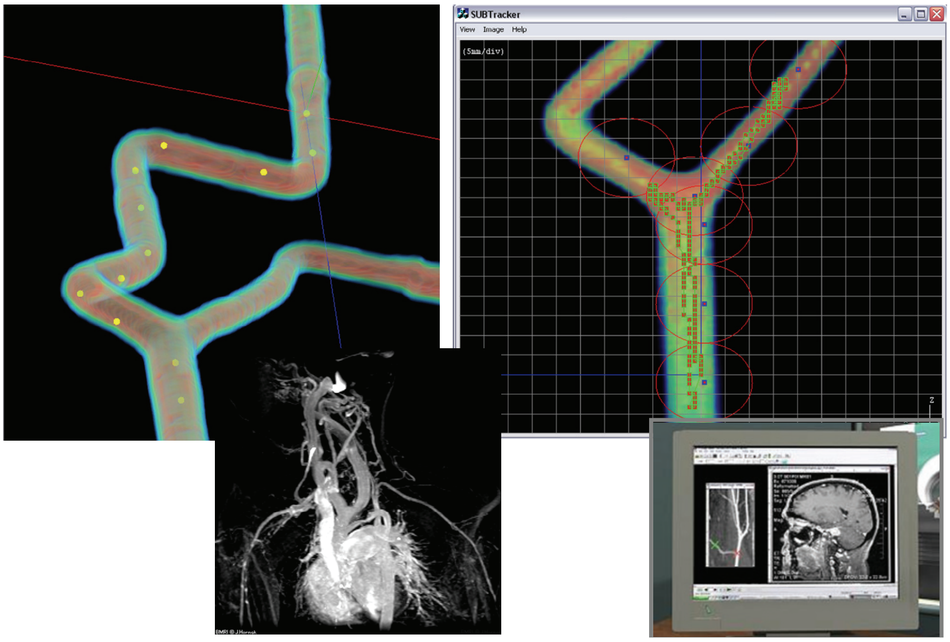

Fig. 3 User interface for trajectory planning in the blood vessels

An example of a user interface for trajectory planning in the blood vessels is depicted in Fig. 3. The images show reconstructed blood vessels obtained from the MRI system. The superposed trajectory with waypoints used to calculate various parameters related to the navigation path of the device, are entered on a computer display. Based on the trajectory, physiological and technical parameters, and a set of rules, propulsion gradients are generated automatically.

Unlike presently known magnetic targeting techniques, the imaging feedbacks and computerized control of 3D magnetic gradient generations (instead of a field from a permanent magnet) provided by a clinical MRI system coped with a carrier based on an agglomeration of nanoparticles made of materials with high saturation magnetization, allow for precise delivery and targeting to sites located deeply in the body. Potential applications include but are not limited to tumour targeting, chemotherapy, chemo-embolization, local hyperthermia, and navigable biosensors.

2.4. Nanorobotic platforms based on robots propelled by bacteria

Our smallest version of each of these robots [4] consists of a micro-structure designed for a specific application being pushed by one MC-1 magnetotactic bacterium (~2 micrometers in diameter) having a chain consisting of 5 to 12 or 14 of a few tenths of nanometers in diameter cubo-octahedral (Fe_3O_4) magnetosomes embedded in each bacterium.

An example of one magnetotactic bacteria pushing a 3 µm bead is depicted in Fig. 4a. It shows a closed-up view of the real implementation using a 3 µm diameter bead demonstrating the displacement of the microrobot in an aqueous solution. By inducing a directional torque on the chain of magnetosomes, the swimming direction of each bacterium can be controlled. This directional torque is typically generated from a small electrical current passing through conductors from various types of dedicated microelectronic circuits and acting under software control algorithms. Examples (recorded in our laboratory using an optical microscope) of computer-controlled bacteria swimming paths are depicted in Fig. 4b and Fig. 4c. Figure 4b shows an example of navigational control of a single bacterium pushing a microbead whereas in Fig. 4c, navigational control of a swarm of magnetotactic bacteria in microfluidic channels is observed under an optical microscope. Swimming speeds reaching 300 micrometers per second for a single MC-1 bacterium without load have been recorded by our group. Each bacterium can provide thrust forces exceeding 4 pN.

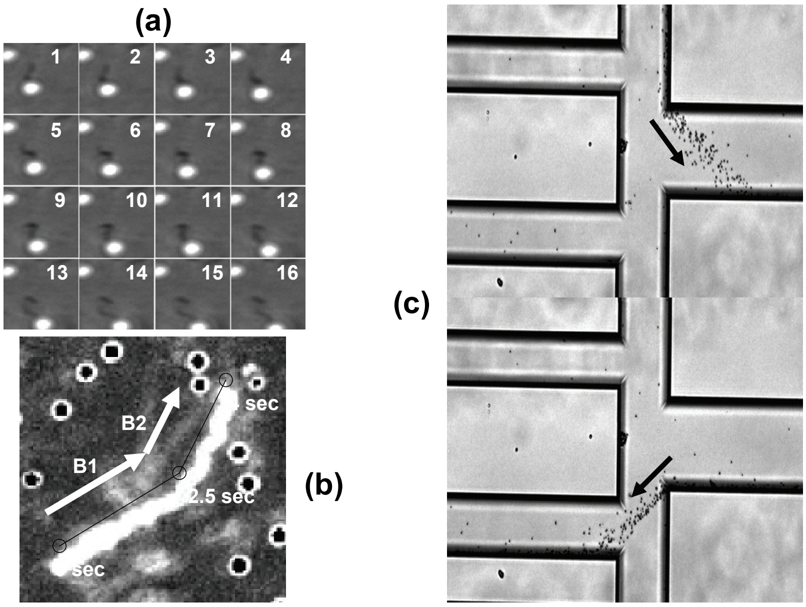

Fig. 4 Control of magnetotactic bacteria used as bio-actuators

Nanorobotic platforms based on these bacteria are being developed by our group for many applications including but not limited to the fast detection of pathogenic bacteria, as biosensors, bio-carriers particularly in micro-fluidic systems, in the concept of bacterial micro-factories (Fig. 5) and high density screening in pharmacology and genetics, for the implementation of fully autonomous aqueous bio-sensing microrobots (Fig. 6), and even for operations in the complex arteriolocapillar networks of the human cardiovascular system.

Figure 5 depicts an example of a platform being developed for implementing the concept of bacterial micro-factory where bacteria are used for manipulating micro-structures for assembly tasks. In Fig. 5a shows the schematic of the microelectronic Integrated Circuit (IC) used as the floor or base of the micro-factory. The schematic shows a grid of conductors spaced 330 nanometers apart and used to generate computer-controlled localized torque, allowing each bacterium to be controlled individually. The implementation of the grid and IC as shown on the computer display is depicted in Fig. 5b with a simplified diagram of the platform in Fig. 5c. The movements and locations of the bacteria are tracked by an optical microscope. Then, through algorithms, small electrical currents are routed through the appropriate conductors in the grid to coordinate the bacteria though local directional torques. An example of the movement of a single bacterium on the grid of the microelectronic circuit as observed under the optical microscope is depicted in Fig. 5d.

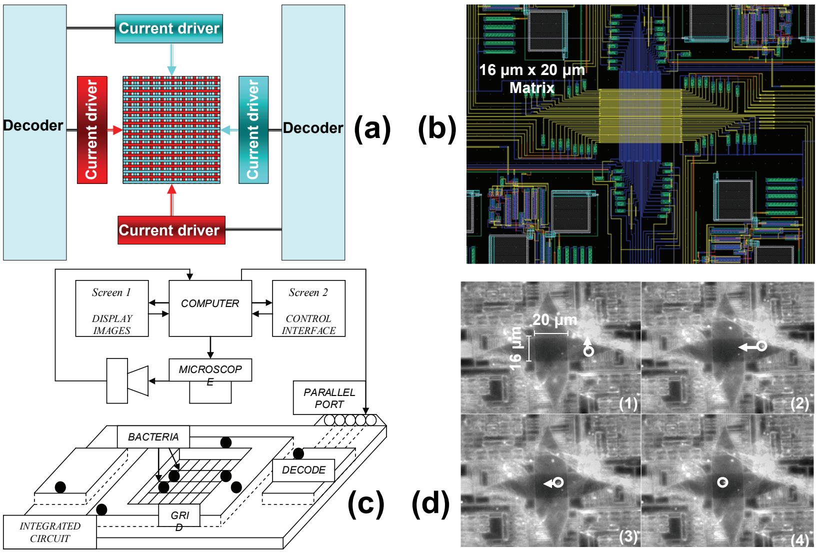

Fig. 5 Example of a platform being developed for implementing the concept of bacterial micro-factory

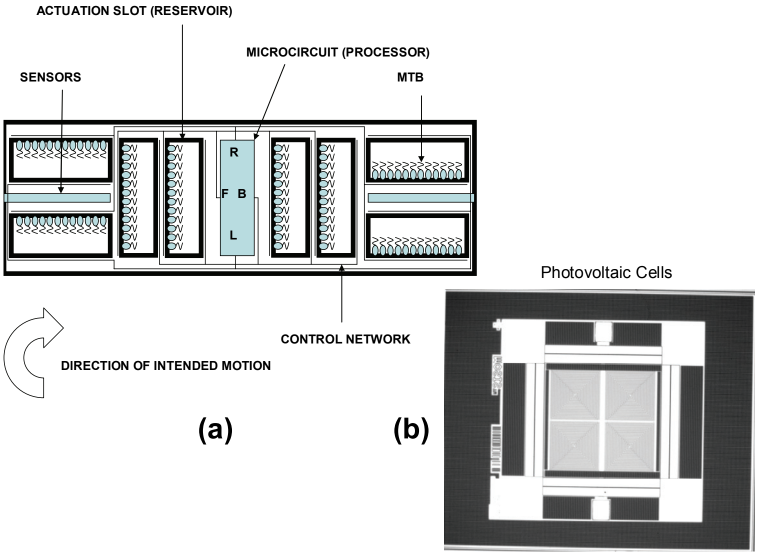

Fig. 6 Schematic of a microrobot a few hundred micrometers long propelled by bacteria

3. CONCLUSION

Nanorobotic instrumented platforms can take various forms. The development process typically requires a highly interdisciplinary approach and in many instances, unconventional components not typically used in engineering must be considered. The use of the MC-1 magnetotactic bacteria is only one example of components that is impossible to match with present modern engineering methods. The design of nanorobots is not only influenced by technological constraints but by the applications and the environment where they must operate. Within this context, several examples of various designs developed in our laboratory have been briefly described.

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NANOROBOTI ZA MIKROFABRIKE, SVE DO OPERACIJA U LJUDSKOM TELU I ROBOTI POKRENUTI BAKTERIJAMA

Sylvain Martel

Eksploatacija osobina na nanoskali fizikalnog sveta omogućava nove platforme i tehnike zasnovane na nanorobotici. U ovom radu su neki specifični interdisciplinarni primeri iz naše istraživačke laboratorije kratko opisani pružajući uvide o mogućnostima i ogromnim potencijalima nanorobotike. Nanorobotika ima veliku primenu u oblasti medicini i bioinženjerstva, uključujući i nove robotske platforme za mikro- i nano-izradu i za visoko zaštićene operacije na nivou fizikalnog sveta nanoskale. Za nekoliko aplikacija gde specifikacije ne mogu da se postignu korišćenjem modernih tehnologija, posebno na tako ekstermno malim skalama, visoko interdisciplinarni pristup integrisanja bioloških komponenti u inžinjerskim sistemima postaje esencijalni deo razvojnog procesa.

Ključne reči: *Operacije nanometarske skale, krvni sudovi, magnetska rezonanca, bakterija u opadanju, magnetotaksija*