Nanofactories based on a fleet of scientific instruments configured as miniature autonomous robots

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Abstract—If the hope for nanotechnology holds true, then we may witness the emergence of new types of high-throughput factories specially conceived to operate at the nanoscale and referred to as nanofactories. It is a very difficult task to predict the exact shape and the various components of such nanofactories. This paper describes a platform that we believe may be the foundation of many future nanofactories. The platform is based on a fleet of scientific instruments configured as miniature autonomous robots, each capable of fast operations at the molecular scale. The proposed approach is briefly compared to other methods and a general description of the final version of such a platform is also provided.

1. INTRODUCTION

Miniaturization in instrumentation generates considerable interest and is becoming a major trend for many applications. Miniature laboratories, for instance, are the latest tools available to scientists aiming at drug discovery based on the knowledge of the human genome. End-users begin to recognize that the laboratory methods in use today will not cope in the medium- and long term, and if they are to remain competitive, other approaches based on miniaturized systems will be necessary [1]. It is now well recognized and established that the use of miniaturized detection systems, for instance, are the trend for the future of biotechnological applications

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with actual emphasis on applications in genomics, drug discovery and molecular
diagnostics.
A next step beyond those miniaturized systems are nanofactories. By treating
atoms as discrete objects to be assembled onto various building blocks in the form
of molecules and assembling these molecules with precise and highly productive
machines, molecular manufacturing could become a reality. As the properties
of all manufactured products largely depend on the arrangement of their primary
building blocks (the atoms), precise control of the assembly process down to the
molecular level by the use of high-throughput molecular assemblers would result
in a significant improvement of the manufactured products. In principle, the laws
of physics and chemistry permit arranging and rearranging of such basic elements
in a huge number of combinations and permutations, allowing one to create
products with new and enhanced properties. Hence, high-throughput nanofactories,
if flexible enough, could have a major impact in many areas, such as materials
and manufacturing, nanoelectronics, medicine and healthcare, the environment,
energy, chemicals, biotechnology, agriculture and information technology [2]. New
methods to manufacture products and new commercial opportunities will emerge
as new techniques become available. Once the techniques are established, the
requirement for high-throughput automation will become one of the key issues for
the successful implementation of nanofactories [3].

The traditional scientific approach in nanotechnology is primarily based on
modeling, simulation and similar tasks using computers, and on experimentation,
characterization, synthesis, etc., using instruments or tools designed to work
at the nanometer-scale. Although the throughput in computation has increased
following Moore’s law (doubling every 18 months), nano-technologists are still
using tools such as single-tip conventional scanning probe microscopes (SPMs) and
the scanning tunneling microscope (STM) (or the atomic force microscope (AFM))
that has a throughput still comparable to the first STM developed more than 20 years
ago. History tells us that throughput in instrumentation is very often a determining
factor in research and development and for commercial applications as well. For
instance, deoxyribonucleic acid (DNA) sequencing was initially performed by hand.
As scientists began to find new applications for DNA analyses, the demand for
faster and more efficient technology increased. Similarly, it is anticipated that many
tasks targeted at the nanometer range will sooner or later require high throughput
automation. As such, effort in the development of high-throughput platforms is
becoming a critical aspect in the field of nanotechnology. Although such platforms
including nanofactories may take various forms, one platform that we believe may
become a reference model for many future nanofactories is briefly described.

2. MOLECULAR ASSEMBLERS

Molecular assemblers or nano-assemblers will most likely be essential parts of the
nanofactories. Assembling atoms and molecules into functional components can be
done using a technique called self-assembly [4] where the process of positioning and arranging atoms or molecules is carried out largely by nature once initiated. Another approach from a much newer field of research is nanomanipulation or positional assembly, using controlled positioning of nanoscale objects. Due to the serial nature of positional assembly, self-assembly appears to be a better approach for high-throughput nanofactories. On the other hand, positional assembly at the molecular scale should enable the synthesis of a much wider range of molecular structures than what is achievable using self-assembly alone. Hence, it is most likely that many future nanofactories may make use of positional control as a supplement to the self-assembly process and, hence, throughput of positional control-based processes is still an important bottleneck to be addressed for future nanofactories.

Two approaches can be considered to improve the throughput of positional control-based processes. The first approach suggests the use of molecular parts or molecular building blocks (MBBs) [5] typically made using self-assembly techniques. Another advantage of using self-assembled MBBs is the extensive set of existing experimental techniques and self-assembled structures already available. Larger MBBs should ease the implementation of cost-effective automation of such molecular assemblers by decreasing the required accuracy in controlled nanomanipulation and by increasing the throughput at the cost of limiting the range of molecular structures that can be synthesized. Hence, flexibility through smaller MBBs could also be a requirement in future nanofactories. To compensate for the decrease in throughput due to an increase of flexibility through smaller MBBs, exploitation of parallelism through the use of many positional control-based nanoassemblers working concurrently is a key element in the development of such nanofactories.

A broad range of possible tools can be used to work at the nanometer range. Among them, SPMs, including the AFM and the STM, are presently the most popular nanoassemblers [6]. Although initially used for imaging purposes, SPMs can also be used effectively for nanomanipulation and different techniques for nanomanipulation have already been developed. One of the first demonstrations of nanomanipulation was done in 1987 at Bell Labs where scientists created nanometer-scale germanium structures on a germanium surface by raising the voltage bias of an STM tip [7].

3. GENERAL APPROACH

The implementation of high-throughput nanofactories based on nanomanipulation is a real challenge, since, as mentioned before, building complex structures one atom, one molecule, or one nanoparticle at a time is very time consuming. A known approach to resolve the serial nature of SPM-based manipulation is the use of large arrays of SPMs on a chip [8], but this approach has some serious drawbacks for many tasks. For instance, performing coordinated assembly tasks where several tips are controlled from the same source may be very challenging. The tasks
performed must be relatively simple since these arrays do not typically provide individual control of each tip. Although very powerful for many applications, such as new techniques for high-density storage, it lacks the flexibility and control needed for more complex and precise nanomanipulation tasks. Most nanomanipulation tasks are very demanding and require a high level of control on each individual tip. Accurate motion of the STM tip relies on calibration of the actuators, which are known to suffer from a variety of problems such as creep, hysteresis and thermal drift of the instrument, which can be quite significant at that scale and independent real-time compensation for these errors artifacts becomes a critical issue.

To improve the control and the precision of the SPM, a few efforts are being made toward the development of nanomanipulators where a conventional single-tip STM or AFM is connected to a force-feedback system, providing the ability to the operator to ‘feel’ the nanoscale objects and hence facilitating the control of more complex tasks at the nanoscale. This approach naturally leads to relatively low speed operations and hence, it will not answer the need for high throughput. It becomes obvious that the next step in this approach will be to use the computer not to mediate the force feedbacks to the operators, but to automate the process without the user’s intervention. Provided that such automation becomes realizable, we would have a fully automated and relatively large conventional single-tip STM platform. To increase throughput, the standard approach would typically connect these platforms in a daisy-chain fashion with conveyors or laboratory robots bringing matrices of samples between successive platforms. However, the unsuitability of this approach for high-throughput operations will appear to be more and more evident as the density of compounds per surface area increases due to several factors including, but not limited to, the lack of degrees of freedom of the nanoscalers and the transport delay between successive nanomanipulators. Although using conveyors or laboratory robots to bring matrices of samples to successive platforms equipped with large arrays of dispensers or tools moving together may work fine in actual high-throughput applications, such as in the pharmaceutical industry, the complexity of many tasks at the nanoscale will require better specifications. These specifications include higher precision, independent motion and the positioning of each tool with individual control, faster throughput and more flexibility. Since the time required at each sequential stage in this pipelined approach is not as predictable at the nanoscale as it is in the macro-world, slight variations in the execution time at any stages would yield significant loss in throughput due to waiting delays, especially for relatively complex tasks. It becomes obvious that reducing the overall size of such SPM-based systems well below the actual size of conventional nanomanipulators would be a huge improvement for works targeted at the nanoscale.
4. PROPOSED PLATFORM

Due to the large number of components and techniques involved, a detailed technical overview of the platform cannot be given in a single paper. As such, only a short overview of the main components and techniques to better appreciate the difficulties in developing such a platform is provided. It is understood that this platform is still under development, but we believe that the stage of research and development is mature enough to provide valuable data about how the final version of such a nanofactory may look like.

The proposed platform is being developed to be adapted for a number of different types of automated research tasks and operations. The objective is to have a versatile system that can be used for many different types of research and applications. As such, our approach leads to the development of a platform \cite{9, 10} based on a fleet of scientific instruments configured as autonomous miniature robots called NanoWalkers \cite{11}. To provide a simple example, our present design allows for more than one hundred of these robots to work on a single platform with a working surface of approximately \(0.8 \text{ m} \times 0.8 \text{ m}\), allowing for more than \(20 \times 10^6\) STM-based measurements/s, assuming that each robot in being equipped with a STM. Because such throughput cannot be handled in real-time by one or more users, the approach naturally leads to tools to automate the scientific method itself where an entire program of research may be carried out by one machine as opposed to a building full of separate machines.

A diagram of the NanoWalker robot is depicted in Fig. 1. Each robot is equipped with an onboard 48 million instructions per second (MIPS) computer (components identified in Fig. 1 as 1, proprietary controller; 2, digital signal processor (DSP); and 3, memory) with a 4 MB/s half-duplex infrared (IR) transceiver for communication with an external central computer. Three piezo-tube actuators (one is depicted in the top right portion of Fig. 1) embedded in each robot and mounted in a pyramidal fashion with the apex pointing upward are used to move the robot between successive locations. Each piezo-leg is controlled independently in all axes by the embedded processor. During travel, the number of steps of the piezo-legs typically varies between 4000 and 10,000 per second with step sizes varying from a few tens of nanometers to a few micrometers. A 12-layer flexible circuit with an overall thickness of approximately 0.5 mm and used to mount and interconnect the embedded electronic components on both sides has been developed and it is shown in the bottom portion of Fig. 1. The circuit is conceived to be bended in a manner shown on the top-right portion of Fig. 1 in order to maintain an overall robot diameter of approximately 32 mm.

Decreasing the overall size of the robot increases the density of instruments per surface area and hence, the overall throughput of the platform. Furthermore, a reduction in throughput due to travel delays is minimized and optimization in dynamic scheduling is much simplified, especially when several types of instruments must be combined in a time-multiplexed fashion on the same samples. This level of flexibility, particularly in combining instruments on the same platform, can represent
Figure 1. CAD representation of the NanoWalker robot (top) and its populated flexible circuit (bottom).
a serious advantage. As opposed to conventional robotic systems using pipelining techniques, the high degree of freedom offered by this approach greatly helps avoiding any reduction in throughput when one robot takes more time to accomplish its task.

Having a fleet of very sophisticated miniature robots operating simultaneously on the same platform requires a special infrastructure capable of supporting and coordinating the robots for maintaining continuous operations at the highest possible throughput. A computer-aided design (CAD) representation of such a platform under development is depicted in Fig. 2. Because of excessive latencies when relying on an external computer, many real-time tasks must be performed by the robot's embedded electronics. Past experiments have shown that the minimum embedded elec-

Figure 2. CAD representation of the nanorobotics platform (top) and the implemented version (bottom).
tronics required to perform such tasks consume in the order of 15 to 20 W. Hence, one of the main problems related to the miniaturization of such high-throughput instrumented robots is that the surface available on each robot to dissipate the heat becomes insufficient. Because traditional heat dissipation techniques are not adequate, since they would typically substantially increase the overall size of each robot, the robots have been designed to work within a special cooling chamber [12] as depicted in Fig. 2. The transition of liquid Nitrogen to a gas state is used to cool a flow of He gas circulating through a coil within a cooling unit (Fig. 2). The high heat conductivity of He helps to minimize the flow rate that may cause excessive thermal drift errors when working at the nanoscale. He is also an inert gas, which provides an atmosphere often suitable for operations at the molecular scale. Each robot has three electronic temperature sensors (one is shown as component 4 in Fig. 1) mounted at strategic locations. Temperature regulation is maintained by communicating information through the IR link between the robots and the central computer (see Fig. 2).

To achieve a higher level of miniaturization, the power is delivered to each robot's embedded electronics from a power unit through a special power floor and the piezo-legs when in contact with the surface. The present version of the power floor consists of alternating positive and negative conducting bands separated by thin insulation bands as depicted in the lower left portion of Fig. 3. Chromium was initially considered to implement the conductive bands, but limitations in the fabrication process within the desired specifications prevented its use. Although several materials could be evaluated, the present implementation uses stainless steel 440C for the conductive bands and granite for the insulation bands. The extremities (feet) of the piezo-legs in contact with the floor are interchangeable and are implemented with a material with a lower hardness coefficient, such as stainless steel 302, in order to minimize structural damages on the power floor. The materials have been selected for their various properties such as hardness, tolerance to oxidation, conductivity or insulation and proper coefficient of friction, just to name a few. As mentioned in Ref. [13], the static coefficient of friction must be selected to match the normal force of each robot in order to achieve self-efficient motion. Unlike previous methods, each NanoWalker robot uses the static force of friction to build up an initial force that leads to a large acceleration of the legs. With a 45° angle combined with synchronized forces between the actuators and using a stick-slip approach, step sizes larger than the maximum amplitude of deflection of the piezo-legs can be achieved, yielding faster displacement rates than what can be achieved with the previous methods. Since no useful work is being done at the molecular scale when an instrumented robot moves between successive locations, fast displacements through an effective embedded locomotion system is a critical issue to achieve higher throughputs through a reduction of travel delays. For instance, past experiments using three four-quadrant 12.5-mm-long (PZT-5A, PZT-5H on the final version) piezo-ceramic tubular actuators on a 8-g prototype, with synthetic ruby at the extremities of each leg in contact with a silicon wafer
with a static coefficient of friction of approximately 0.35 (oxidation layer removed) between the legs and the surface, showed a maximum displacement of 200 mm/s when actuated at approximately ±40 V and using 4000 steps/s with step size of approximately 50 μm. The present final wireless version of the NanoWalker robot has a mass four times the mass of the wired prototype at 32 g because of the embedded electronics but the actuation voltage level has been increased to ±150 V with the coefficient of friction adjusted accordingly although past experiments have shown that an increase in mass in such a range has no great impacts on the overall motion of the robot due to a proportional increase of the force of the piezo-legs caused by an increase of the normal force. More details on the issues related to the locomotion system are given in Ref. [13].

The position of each robot within the entire area to within a few micrometers of resolution is presently achieved by detecting signals sent by the IR emitters on each robot (see Fig. 1), using position sensing detectors (Fig. 3). The power floor is divided onto four working cells, each cells being supported by one infrared positioning and communication unit as described in Ref. [14]. Atomic level

![Figure 3](image)

**Figure 3.** CAD representation showing inside the cooling chamber with the position sensing detectors (PSD, top left), section of the power floor with conducting bands, working zones and atomic grids (bottom left), view of a few atomic grids with the engraved lines for encoding or addressing (top-right), image of the atomic structures obtained with the STM (bottom right), view of the atoms from the STM (bottom middle). Not to scale unless specified.
positioning capability is achieved by ‘counting’ atoms with the embedded STM on recently developed atomic grids (isolated from the power rails) with special references and patterns, a few nanometers wide, engraved on a surface of highly oriented pyrolytic graphite (HOPG). This is shown in Fig. 3. An image of the atomic arrangement of a surface is obtained through a finely sharpened tungsten wire (the STM tip) by sensing corrugations in the electron density, which is dependent of the positions of surface atoms. When the tip-surface separation is reduced sufficiently (typically within 2 nm), as explained by the principles of quantum mechanics, electrons ‘tunnel’ through the tip-surface separation. By applying a small voltage (bias) at the tip-surface separation, it results a net current of electrons (referred to as tunneling current) that flows through the tip-surface separation in the direction of the bias. A four-quadrant piezoelectric tube transducer embedded onto the NanoWalker is used to raster the tip across the surface. While scanning the surface, corrugations in the electron density at the surface cause corresponding variations in the tunneling current. The tunneling current is then amplified and converted in digital form prior to be accessed by the embedded processor. By detecting small variations in tunneling current or by maintaining the tunneling current constant through feedback controls, a two-dimensional map of the corrugations in electron density at the surface can be derived [15]. Because of limitations in the dynamic range of the recording electronics and constraints related to the piezo-actuators including but not limited to their smaller dimensions and the maximum voltage that can be safely applied, the maximum scanning surface while in working mode (i.e. with maximum resolution) is presently limited to approximately ±80 nm (nm).

In the ‘atomic positioning mode’, in order to link the positioning at the atomic scale with the optical-based positioning system through the limitations in the fabrication process of our atomic-referencing grid, the scan range is extended to approximately ±1.6 nm, maintaining the overall dynamic range constant while fulfilling the Nyquist criterion by providing sufficient readings per lattice to efficiently ‘count’ atoms. Past experiments with the present implementation of the PSD system have shown that the approximately 400 ms of integration time was required to obtain a position at ±1.6 nm and that the system was very sensitive to external noises. To accelerate the positioning process while making the system more robust, several grids (3.2 μm × 3.2 μm each) are implemented within each HOPG surface of approximately 30 μm × 30 μm where each grid is uniquely identified by a code. As shown in the top-right portion of Fig. 3, various line widths with increments of 62.5 nm have been engraved using a focus ion beam (FIB) process. By detecting the widths through the use of the STM, it is possible to identify a single atomic grid. Once located on a specific grid, the STM begins ‘counting’ atoms from a reference point. Once positioned, the work at the atomic or molecular scale begins. Once the work is completed, the robot informs the central computer through the IR communication link and then moves to the next assigned location.
5. SOME POTENTIAL APPLICATIONS AND MAJOR CONSTRAINTS

Although an STM is initially considered as a first instrument to be embedded onto the NanoWalker robot, various instruments analogous and/or derived from the STM could potentially be embedded as well, providing opportunity for a larger set of applications. The list of such instruments includes the AFM, lateral force microscope (LFM), STM, magnetic force microscope (MFM), scanning capacitance microscope (SCM), electric force microscope (EFM), magnetic resonance force microscope (MRFM) and many more. For the STM alone, some very common applications are in the fields of surface sciences and in metrology where nano-topography of a surface or instance is essential for many applications where surface finish is crucial, such as for high precision optical components, or to investigate surface deposition, etc. In other applications, the high spatial resolution of STM provides an important complement to other imaging systems, such as the scanning electron microscope (SEM). New applications and, therefore, new opportunities for nanofactories may occur from results of research activities worldwide. For instance, for fabricating nanoscale structures with a platinum tip of an STM, ultra-small nanodots of about 1 to 2 nm in diameter can be reproducibly created on Si(111)7 × 7 surface by applying repetitive pulses with the right voltage and pulses duration (e.g. +3 V for 5 ms) [16]. STM has also been used for nanomanipulation and deposition processes and other types of applications are also possible. Furthermore, by combining several instruments on the same samples, more complex applications may be supported. Multi-probes systems, such as STM-based matrices, are still a valuable approach [17] for many applications to increase throughput and such matrices could also be potentially embedded onto each instrumented robot if deemed necessary, potentially providing enhanced flexibility through combining instruments on the same platforms.

Although many applications are possible with the proposed nanorobotic platform, providing enhanced flexibility and higher throughput, some major constraints exist at the present time but further researches are underway to resolve these issues. One major constraint is the environmental temperature in the chamber and which is set to maintain the fleet of instrumented robots in the operational state. Although this range of temperature levels might not be ideal for all applications, it is likely to be possible to adjust the thermal resistance between the robots and the environment through other types of gaseous atmospheres. For applications at room temperature, other approaches are possible, for instance using water evaporation in air (liquid boiling convection), can be implemented [18], but this approach as several drawbacks, as mentioned in Ref. [19]. For high heat conductivity, the dielectric of He in the present implementation makes the prevention of arcing more difficult, especially with further miniaturization of the physical features of the robots coped with high voltage levels. This also holds true during motion. Although a special arcing control circuit has been implemented to prevent erosion on the extremities of the piezo-legs and on the power rails during motion, making repeatability in displacement very difficult especially for smaller step sizes, the use of He compared
to air makes it more difficult to avoid arcing when the legs are in motion. Although AC power modulation would avoid arcing, the size of the embedded capacitors required to regulate the AC voltage level to a precise DC level for the embedded electronics would be too large. In order to reduce the size of the capacitors, a higher modulation frequency could be used but it would most likely induce noises on the sensitive embedded instruments. Although there are still issues to be improved, the approach has several major advantages such as the higher resonant frequency of the instrumented robots, making the instruments less sensitive to a much larger band of low frequency vibrations.

6. CONCLUSIONS

A version of a platform that could be a reference model for future nanofactories has been briefly described. To cope with the various constraints and uncertainties when working at the nanoscale and to provide flexibility, the platform relies on a fleet of independent autonomous instrumented robots, each capable of molecular-scale operations. To maintain maximum throughput, the platform is designed to operate with minimum user's interventions. An infrastructure especially designed to support such an approach, by providing cooling facilities, coordination, positioning and power, has been introduced.

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international committees. He was born in Quebec City, Canada, and pursued graduate studies in electrical engineering at McGill University, Canada, and post-doctoral studies at MIT. His main research interests include the development of platforms based on miniature instrumented robots for operations at the nanometer-scale, the conception of new brain-machine interfaces, minimally invasive tools based on microdevices propelled in the blood vessels by magnetic gradients generated by Magnetic Resonance Imaging (MRI) systems, MEMS and SoC-based miniature robots, the integration of bacteria as components in MEMS/NEMS, and several other related research projects.

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