Large-Scale Nanorobotic Factory Automation Based on the NanoWalker Technology

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Abstract **– The emerging fields of nanosciences and nanoengineering will provide the ability to work at the molecular level to create larger structures with new molecular organization. This understanding and control over the fundamental building blocks of all physical entities will lead to new emerging opportunities in factory automation. Although research in this field is very active, little has been done toward increasing the throughput rate, a factor that will be critically important in future nanofactories. An approach for the implementation of scaleable and high-throughput nanofactories based on a fleet of miniature autonomous robots capable of operations at the atomic-scale is described.**

I. INTRODUCTION

All manufactured products are made of atoms, and the properties of those products largely depend on the arrangement of these atoms. Modern macroscopic manufacturing methods such as casting, milling, welding and all other traditional manufacturing methods including lithography are crude and imprecise from a molecular point of view since they spray atoms in great statistical herds. Molecular manufacturing on the other hand could allow precise control of the assembly process down to the molecular level. With these high-throughput molecular assemblers, almost all manufactured products could be improved, some by several orders of magnitudes. Since the laws of physics and chemistry in principle permit arranging and rearranging the elements in so many combinations and permutations, such high-throughput nanofactories, if flexible enough, could produce a multitude of different products.

Hence, the developments in the emerging fields of nanosciences and nanoengineering are most likely to change the methods used to manufacture almost all future products. Although the methodology to operate at the nanoscale is still at its infancy, significant progress is expected in the not-too-distant future. With these new methods, new commercial opportunities will emerge and the requirement for high-throughput automation will become one of the key issues for the successful implementation of nanofactories, or factories operating at the nanoscale.

Some of the areas [1] where high-throughput automation at the nanoscale is likely to have a significant impact include, but are not limited to, materials and manufacturing, nanoelectronics, medicine and healthcare, the environment, energy, chemicals, biotechnology, agriculture, and information technology.

Nanotechnology is being pursued along two converging directions: top-down and bottom-up. The present semiconductor fabrication techniques, for instance, use a top-down approach for producing smaller structures. Current optical lithography techniques [2] have obvious limitations [3] due to the wavelength of visible light (in the order of 500 nanometers (nm)). Although X-ray and electron-beam (E-beam) lithography will reduce feature sizes further, despite the great increase in complexity and cost of fabrication, these techniques are still limited and not very promising for implementing future nanoscale structures.

An alternative is to adopt a bottom-up approach by assembling atoms and molecules into functional components and systems. This can be done using a technique called self-assembly [4] or by nanomanipulation or positional assembly, using controlled positioning of nanoscale objects. Presently, the self-assembly approach has severe limitations in the development of nanoscale objects, and the structures produced tend to be highly symmetric. Furthermore, the most versatile self-assembled systems are organic and therefore generally lack robustness. Positional control, on the other hand, allows the construction of any structure, including highly asymmetric shapes, permissible within the laws of physics. In other words, positional control allows a relatively high degree of control over where each individual atom or molecule is placed. Whereas in self-assembly, the process of positioning and arranging atoms or molecules is carried out largely by nature once initiated.

As described in this paper, the proposed nanofactory will rely heavily on positional control and will provide flexibility and control over a large range of possible tasks. Despite a large number of nanoassemblers working concurrently, while minimizing the complexity of the manufacturing platforms to increase throughput, self-assembly may still be a valuable method to be integrated

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within the same environment for building self-assembled symmetrical parts prior to being assembled into more complex molecular structures using positional control.

II. TOOLS FOR NANOMANIPULATION

Although a broad range of possible tools can be used to work at the nanometer range, scanning probe microscopes (SPMs) [5], including atomic force microscopes (AFMs) and scanning tunneling microscopes (STMs), are the most popular nanoassemblers at the present time. In all cases, the platform must at least be capable of positioning the tools to less than half an atomic diameter. As a simple example, removing hydrogen atoms on a diamond (111) surface requires positional accuracy of at least 0.1 to 0.2 nm (1 to 2 angstroms) since the distance between adjacent hydrogen atoms is about 0.25 nm (2.5 angstroms). Work with STMs, for instance, clearly shows that it is possible to achieve the required accuracy and beyond [6].

Although initially used for imaging purposes, SPMs can also be used effectively for nanomanipulation. 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]. Because of its relative simplicity, the STM technique is the first one being implemented on the nanofactory described here.

A first simple technique for nanomanipulation with an STM uses pushing and pulling. The technique is most suitable for constructing 2-D structures, of which there exist many examples [8]. Inter-atomic attractive forces can be used, where the STM tip is placed sufficiently close to an atom for the attractive force to be larger than the resistance to lateral movement. The atom is then pulled along the trajectory of the tip. Lateral repulsive forces can also be used in some cases.

Another technique that is sometimes applicable is based on picking and placing much like pick-and-place operations in industrial macrorobotics. In this process, an STM tip is moved sufficiently close for the absorption barriers of the surface and tip to be comparable. An atom may leave the surface and become absorbed by the tip, or vice-versa. Due to electromigration caused by the electric current flowing in the tunneling junction, Xenon atoms can be transferred between an STM tip and a nickel surface by applying voltage pulses to the tip [8]. Other mechanisms such as field-induced evaporation, perhaps aided by chemical phenomena at the tip/surface interaction can be used for other types of atoms (e.g. silicon atoms between a tungsten tip and silicon surface) at room temperature by applying voltage pulses to the tip [9, 10]. Research now underway will most likely offer other methods of nanomanipulation suitable to future nanofactories.

III. HIGH-THROUGHPUT PLATFORMS

The implementation of high-throughput nanofactories is a real challenge since building complex structures one atom or one nanoparticle at a time is very time consuming. Exponential manufacturing may be one technique where an SPM is used to construct structures that are capable of self-replication (e.g. DNA) but it is a very constrained approach at the present time. A more versatile approach, to resolve the serial nature of SPM-based manipulation, is the use of large arrays of SPM on a chip such as the one developed at Cornell University [11]. Performing coordinated assembly tasks where several tips are controlled from the same source may be a very challenging task. Furthermore, the surface must be very flat and the tasks performed must be relatively simple since these arrays do not provide individual control of each tip. In addition, these systems are not very flexible since the work areas are dependent upon the spacing between the STM tips in the same array. Therefore, although it is a very powerful approach 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 an 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 and hysteresis. In addition, thermal drift of the instrument can be quite significant when at room temperature, where a drift of one atomic diameter per second is common. Compensation for these error artifacts, especially for massively parallel operations, must be automatic and hence requires high-performance processing.

IV. NANOWALKER PLATFORM

A. Instrumented Miniature Robot

The present version of the proposed large-scale nanofactory based on the NanoWalker technology [12-16] consists of several platforms where each platform [17] can have more than 100 miniature wireless robots each equipped with an instrument, in this case an STM tip as depicted in Fig. 1.

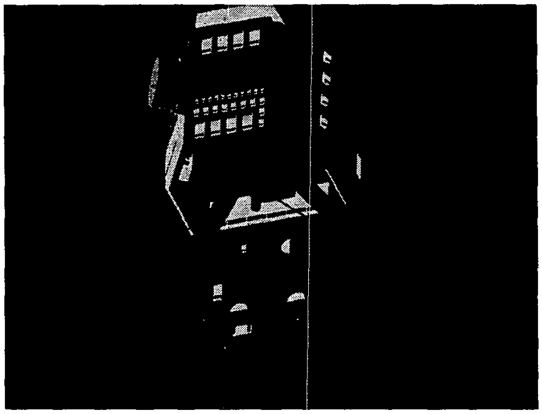

Fig. 1. Bottom view of the present version of the NanoWalker robot with the flexible circuit unwrapped to show the STM and the legs.

Each robot is approximately 32 mm in diameter. The overall size of the robot is critical on such a platform, since the working surface or floor of each platform is limited to 0.5 meter in maximum diameter. These limitations are due to the line of sight of the fast infrared positioning and communication systems operating at the maximum rate of 4 Mb/s at a maximum distance of 1 meter above each robot's embedded infrared transceiver. A higher level of miniaturization means that more robots can operate simultaneously on the same platform. A larger number of robots yields a higher throughput per platform and hence, a lower implementation cost with less total space required on the factory floor.

In order to implement the functionality and performance required to execute complex tasks at the nanometer scale, several advanced integration and assembly techniques [18, 19] have been used to achieve sufficient levels of miniaturization. Due to the communication latency, and the computer's long response time, relying on an external computer to perform most of these tasks was not an option. Therefore, several hundred electronic and mechanical components had to be embedded onto each robot in order to achieve the throughput and latency requirement for each robot.

B. Power Distribution

Experiments [20, 21] have shown that precision in displacement, especially in the nanometer range of the tethered versions of a NanoWalker type, was not consistent due in large part to the stiffness of the tiny wires. For this reason, and to avoid tangling the wires among a large group of robots operating within a small workspace, a wireless version of the robot was required. As each robot is to perform complex tasks at high speed, high-powered electronics were embedded onto each robot. After a long survey of all power distribution options and miniature power sources, a new power distribution scheme has been developed where each robot is powered through the legs when in contact with the working surface or power floor [22], as shown in Fig. 2.

The power floor is a 0.5-meter diameter workspace within a rectangular metal plate made of alternating layers of positive and negative power bands separated by buffer zones. The buffer zones prevent electrical shorts during transitions of a leg between two successive power bands. The geometry of the power bands are designed with regard to the size of the NanoWalker robot such that at least one of the three legs of each robot is in contact with a positive band while at least another leg is in contact with a negative band in order to ensure electrical current to flow through each robot's embedded electronics. A bridge rectification circuit embedded onto each robot allows each leg to make contact with either a positive or negative band. A voltage between 6.5 and 12 VDC is typically used across the power floor. Voltage is regulated onboard each robot to lower voltage levels to the electronics and up to ±150 Volts in order to maximize the deflection amplitude of the piezo-actuators. A low voltage across the power floor minimizes problems related to sparking. When a robot is "walking" [23] several thousand steps per second, sparks occur due to the small gap between the feet and the surface. These sparks damage both the feet and the surface, preventing consistency in the motion especially at the nanometer range. Therefore, a power shutdown mechanism under microprocessor control has been integrated onto each robot and is activated during each step. During this short shutdown period, an onboard capacitor provides temporary power to the electronics. Depending on the motion, a larger voltage on the power floor is required for the longer discharge time of the onboard capacitor.

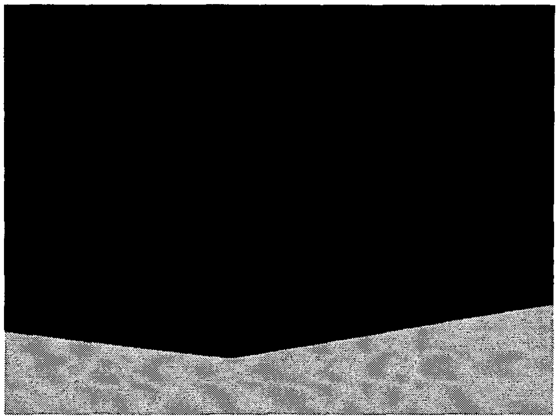

Fig. 2. The diagram shows NanoWalker robots working on the power floor.

The surface of the power floor is coated with a thin film of Chromium. Chromium was selected for its physical characteristics such as good electrical conductivity, low static coefficient of friction (appropriate to the normal forces or mass of each robot and for optimal motion), resistance to oxidation (preventing modifications of the coefficient of friction and causing changes in the motion), and its mechanical hardness (which prevents any damage to the surface caused by the impact of the legs during motion and which might prevent subsequent precise motions of the robots).

The power floor has also special working regions called the neutral zones. The neutral zones are conducting regions embedded in the power floor. The neutral zones are not electrically connected to the power distribution scheme, allowing STM-based operations to be performed. Such neutral zones occupy most of the surface of the power floor and maximize the density of working sites, since the legs of the robots can be guided between the neutral zones with great accuracy.

C. Heat Dissipation

The power dissipation of each robot is relatively high due to the tasks that must be supported by each of these robots. These tasks include walking several thousand steps, positioning itself, communicating at 4 Mb/s, and performing 200,000 precise measurements per second at the nanoscale. All of these tasks are controlled by an embedded computer capable of executing 48 million instructions per second.

The power dissipation of the NanoWalker robot will vary according to the tasks and internal resources being used. In the present design, power dissipation of each robot is expected to be on the order of 10 to 20 Watts. To increase the future capability of the robot, a special expansion port is embedded. Along with the expanded capability, the NanoWalker robot is presently designed to accept a maximum input voltage of 12 VDC with a maximum current of 3 Amperes, corresponding to a maximum power consumption of 36 Watts per robot. As the size of the robot decreases, the surface area available to dissipate heat becomes insufficient and the temperature rises beyond the maximum operating temperature of the embedded electronics. To operate correctly, the temperature range of the NanoWalker embedded electronics is limited to 0°C to 70°C.

Conventional heat dissipation methods, including heat sinks and heat pipes, would substantially increase the overall size of the robot. In order to maintain the robot to a minimum size, other heat dissipation techniques have been developed [24].

One approach consists of using water evaporation to efficiently dissipate the heat. In this approach, each robot wears a special "jacket", approximately 1 mm thick, containing water. Experiments have shown that the operating time of each robot could be extended from a few seconds to a couple minutes, worst case, when operating at room temperature. One of the major drawbacks of this approach is that the robots need frequent refills, allowing little time for each refill when a large number of robots operate on the same platform.

The best approach so far consists of encapsulating the robots in a cooled chamber filled with an inert gas, in this case helium because of its good thermal conductivity (about six times the thermal conductivity of air). Although many applications at the nanoscale are performed in air at room temperature, several applications requires vacuum at room temperature to decrease large vibrations of certain molecules. Because it is not possible to evacuate effectively heat in vacuum, similar results may be obtained using inert gases. To keep the overall size of each robot to a minimum, a metal sheet (copper or silver) is mounted on the robot's electronics and is encapsulated in such a manner that the internal temperature inside each robot is maintained relatively constant while still being higher that the temperature in the chamber. Temperature sensors embedded in each robot allow continuous monitoring of the internal temperature. Before the robot's temperature can rise or fall beyond the acceptable range of operation, a message is sent from the robot to the central computer (through the infrared communication scheme) and the cooling system for the chamber is adjusted accordingly. Lowering the temperature also helps to minimize the vibration of the molecules. The wall of the chamber is made of a metal with good thermal conductivity and may be cooled with the aid of a chiller and water pipes in order to evacuate up to a maximum of 3 kW per platform; thus providing a maximum throughput of 20 million STM-based operations per second executed among 100 NanoWalker robots.

D. Positioning Systems

The positioning tasks on each platform rely on two positioning systems: the global scale positioning system (GSPS) and the atomic scale positioning system (ASPS). The GSPS [25] is located on top of the platform and senses infrared signals sent through infrared (IR) transmitters located on each robot as shown in Fig. 3.

These transmitters, flashing one at a time, are placed far apart to maximize angular accuracy. Positioning time varies from a few microseconds during travel time to more than 500 milliseconds of integration time (necessary to achieve the best accuracy required for final positioning) just prior to switching to the ASPS system. During travel, positioning information is provided by the GSPS to each robot, with the positions of other robots such that corrective actions performed by each robot's embedded computer can be done to achieve a minimum travel time while avoiding other robots.

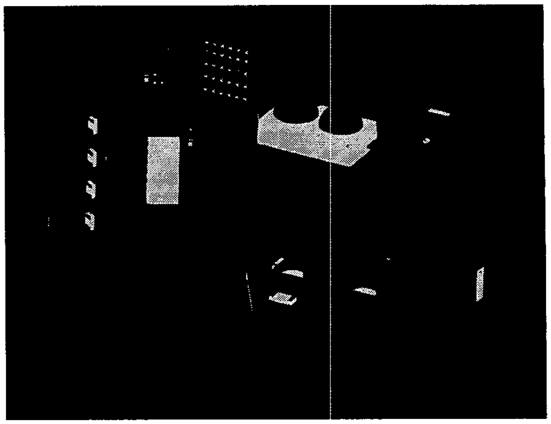

Fig. 3. Diagram of the present version of the NanoWalker robot showing the infrared position transmitters with a section of the flexible circuit unwrapped.

Once guided with the GSPS to the final destination, each robot switches to the ASPS mode. The ASPS mode uses surface features and the STM tip [26] to determine its position. Atomic resolution in the ASPS mode is achieved by "counting" the number of atoms from pre-reference sites. Due to several constraints such as the limitation on the maximum voltage allowed in order to avoid depolarization of the scanning tube, and the limit in the dynamic range of the embedded electronic converters, as well as the space available limiting the maximum length of the STM, an accuracy of at least ±2.1 micrometers from the GSPS was required to match the maximum deflection of the STM tip while providing enough scanning resolution to detect each atom. Once at its final destination, the maximum scanning range of the STM tip is decreased substantially in order to increase atomic resolution.

E. Platform

A simplified diagram of a NanoWalker platform is depicted in Fig. 4. The throughput of this single platform can vary from 200,000 STM-based operations per second at the nanoscale (with a single robot) to beyond 20 million operations per second with more than 100 NanoWalker robots (working concurrently).

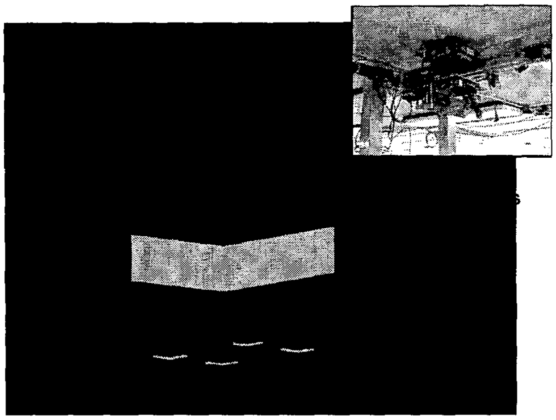

Fig. 4. Simple diagram of the NanoWalker platform with a picture of the GSPS system.

A single platform could support a variety of operations simply by using robots which contain a variety of instruments. In addition, because of the accuracy of the ASPS, grouped robotic tasks at the molecular level can be realized.

For applications exceeding the maximum throughout possible using a single platform, a multi-platform configuration such as the one shown in Fig. 5 may be the solution.

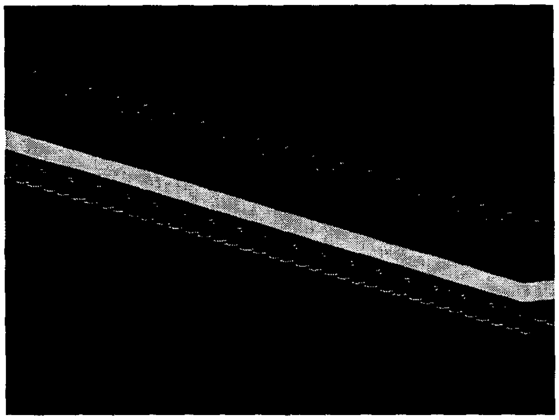

Fig. 5. A simple example of a NanoWalker multi-platform configuration for large-scale nanofactories.

In Fig. 5, power floors are transferred to the next platforms through a conveyor system. Before moving the power floor, the NanoWalker robots move to a fixed adjacent floor until the next power floor (with the new samples) arrives. This configuration could offer a very flexible, yet modular manufacturing system for many mass-scale operations at the nanoscale.

V. CONCLUSION

As nanosciences and nanoengineering progress and new techniques are developed, high throughput operations will become a determining factor in transferring this technology to the manufacturing sector. So far, much of the research activities in nanotechnology have been conducted in finding new manipulations and synthesis techniques, with little effort toward increasing the throughput at which these operations must be performed in order to be commercially viable. This paper suggests a platform based on a colony of very sophisticated instrumented robots called the NanoWalkers. Although not at its final stage, the development of such a platform is progressing at a very fast pace and offers a different and promising approach to mass-scale operations at the nanoscale level.

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REFERENCES

[1] "National Nanotechnology Initiative: The Initiative and its Implementation Plan". *National Science and Technology Council, Committee on Technology, Subcommittee on Nanoscale Science, Engineering and Technology*, USA, 144 pages, July 2000.

[2] Rai-Choudhury P. and Lin Burn J. "Handbook of Microlithography, Micromachining, and Microfabrication: Microlithography". *Book News, Inc.*, Vol. 001, Portland, OR, USA, 776 pages, June 1997.

[3] Keyes R.W. "Miniaturization of the Electronics and its Limits". *IBM Journal of Res. Development*, Vol. 32, No. 1, pp. 24-28, Jan. 1988.

[4] Fujita M., Bernt I., Bogge A.J., and Carr A.J. "Molecular Self-Assembly: Organic Versus Inorganic Approaches". *Springer Verlag*, 1st Edition, 254 pages, May 15, 2000.

[5] Wiesendanger R. "Scanning Probe Microscopy and Spectroscopy". *Cambridge University Press*, Cambridge, UK, 1994.

[6] Eigler D.M. and Schweizer E.K. "Positioning Single Atoms with a Scanning Tunneling Microscope". *Nature 344*, pp. 524-526, April 5, 1990.

[7] Becker R.S., Golovchenko J.A., and Swartzentruber B.S. "Atomic-scale Surface Modifications using a Tunneling Microscope". *Nature*, Vol. 325, No. 6103, pp. 419-421, Jan. 29, 1987.

[8] Stroscio J.A. and Eigler D.M. "Atomic and Molecular Manipulation with the Scanning Tunneling Microscope". *Science*, Vol. 254, No. 5036, pp. 1319-1326, Nov. 29, 1991.

[9] Lyo I.W. and Avouris P. "Field-induced Nanometer- to Atomic-scale Manipulation of Silicon Surfaces with the STM". *Science*, Vol. 253, No. 5016, pp. 173-176, July 12, 1991.

[10] Uchida H., Huang D.H., Yoshinobu J., and Aono M. "Single Atom Manipulation on the Si(111)7×7 Surface by the Scanning Tunneling Microscope (STM)", *Surface Science*, Vols. 287/288, pp. 1056-1061, 1993.

[11] Spallas J.P. and MacDonnald N.C. "Self-aligned Silicon Field Emission Cathode Arrays formed by Selective, Lateral Oxidation of Silicon", *Journal Vac. Sci. Technol.*, Vol. B11 (2), pp. 437-440, Mar./Apr. 1993.

[12] Martel S., Cervera Olague L., Bautista Coves Ferrando J., Riebel, S., Koker T., Suurkivi J., Fofonoff T., Sherwood M., Dyer R., and Hunter I. "General Description of the Wireless Miniature NanoWalker Robot Designed for Atomic-scale Operations" *Proceedings of SPIE: Microrobotics and Microassembly*, Newton, MA, Oct. 29-31, 2001.

[13] Martel S., Sherwood M., Helm C., Garcia de Quevedo W., Fofonoff T., Dyer R., Bevilacqua J., Kaufman J., Roushdy O., and Hunter I. "Three-legged Wireless Miniature Robots for Mass-scale Operations at the Sub-atomic Scale", *Proceedings of the 2001 IEEE International Conference on Robotics and Automation: From Microrobotics to Nanorobotics*, Seoul, South Korea, May 21-26, 2001.

[14] Martel S., Roushdy O., and Hunter I. "Miniature Instrumented Robots for Mass-scale Synthesis and Characterization", *Proceedings of the 1st Annual International IEEE EMBS Special Topic Conference on Microtechnology in Medicine and Biology: MicroInstrumentation*, Lyon, France, pp. 160-164, Oct. 12-14, 2000.

[15] Martel S., Bevilacqua J., Dyer R., Fofonoff T., Garcia de Quevedo W., Helm C., Sherwood M., and Hunter I. "Development of a Miniature Three-legged Bio-instrumented Autonomous Robot", *Proceedings of the IEEE-EMBS Asia-Pacific Conference on Biomedical Engineering*, Hangzhou, China, pp. 513-514, Spet. 26-28, 2000.

[16] Martel S., Madden P., Sosnowski L. Hunter I., and Lafontaine S. "NanoWalker: A Fully Autonomous Highly Integrated Miniature Robot for Nano-scale Measurements", *Proceedings of the European Optical Society (EOS) and SPIE International Symposium on Envirosense, Microsystems Metrology and Inspection*, Vol. 3825, Munich, Germany, 12 pages, June 14-18, 1999.

[17] Martel S., Koker T., Riebel S., Sherwood M., Suurkivi J., and Hunter I. "An Infrastructure Suited for Supporting a Fleet of Wireless Miniature Robots Designed for Atomic-scale Operations", *Proceedings of SPIE: Microrobotics and Microassembly*, Newton, MA, USA, Oct. 29-31, 2001.

[18] Martel S., Doyle K., Martinez G., Hunter I., and Lafontaine S. "Integrating a Complex Electronic System in a Small Scale Autonomous Instrumented Robot: The NanoWalker Project", *Proceedings of SPIE, Microrobotics and Microassembly*, Vol. 3834, Boston, MA, USA, pp.63-74, Sept. 21-22, 1999.

[19] Martel S., Bautista Coves Ferrando J., Cervera Olague L., Fofonoff T., and Hunter I. "Implementing Frequency Modulated Piezo-based Locomotion for Achieving Further Miniaturization for Wireless Robots", *Proceedings of SPIE: Microrobotics and Microassembly*, Newton, MA, USA, Oct. 29-31, 2001.

[20] Martel S., Szabelski M., Leija A., Madden P., Lafontaine S., and Hunter I. "Initial Results of a New Type of Locomotion for a Wireless Instrumented Robot Capable of Subatomic Movements", *Proceedings of the Biomedical Engineering Society and the 21st Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Atlanta, GA, USA, Oct. 13-16, 1999.

[21] Martel S., Saraswat A., Michel A, and Hunter I. "Preliminary Evaluation and Experimentation of the Push-slip Method for Achieving Micrometer and Sub-micrometer step sizes with a Miniature Piezo-actuated Three-legged Robot Operating Under High Normal Forces", *Proceedings of SPIE: Microrobotics and Microassembly*, Vol. 4194, Boston, MA, USA, pp. 141-148, Nov. 5-6, 2000.

[22] Martel S., Garcia de Quevedo W., and Hunter I. "Techniques for Continuous Power Delivery to a Group of 15-Watt +3.3 to ±150 VDC Miniature Wireless Instrumented and Fast Stepping Robots Through Several Thousand Intermittent Contacts per Second Between the Robots' Legs and the Walking Surface", *Proceedings of SPIE: Microrobotics and Microassembly*, Vol. 4194, Boston, MA, USA, pp. 168-177, Nov. 5-6, 2000.

[23] Martel S., Saraswat A., and Hunter I. "Fundamentals of Piezo-ceramic Actuation for Micrometer and Sub-micrometer Motions for the NanoWalker Robot", *Proceedings of SPIE: Microrobotics and Microassembly*, Vol. 4194, Boston, MA, USA, pp. 82-93, Nov. 5-6, 2000.

[24] Martel S., Embler J., Riebel S., Gibbons J., and Hunter I. "A Novel Heat Dissipation Approach for High-powered Miniature Robots", *Proceedings of SPIE: Microrobotics and Microassembly*, Newton, MA, USA, Oct. 29-31, 2001.

[25] Martel S., Roushdy O., Sherwood M., and Hunter I. "Optical High-resolution Positioning System for Miniature Robot", *Proceedings of SPIE: Microrobotics and Microassembly*, Vol. 4194, Boston, MA, USA, pp. 121-128, Nov. 5-6, 2000.

[26] Martel S., Koker T., and Hunter I. "Main Issues for Embedding onto a Wireless Miniature Robot, a Scanning Tunneling Positioning System Capable of Atomic Resolution over a Half-meter Diameter Surface Area", *Proceedings of SPIE: Microrobotics and Microassembly, Newton, MA, USA, Oct. 29-31, 2001.*