Cooling Platform for an Automated Nanofactory Based on a Fleet of Miniature Robots Designed for Atomic Scale Operations

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ABSTRACT

The development of scientific instruments configured as wireless miniature robots capable of operations at the atomic scale may provide a solution for high throughput mechanosynthesis processes in nanotechnology. To this end, a nanofactory based on the coordinated work of a fleet of approximately 100 of these instrumented robots is being built. To achieve a high density of instruments and to increase both the throughput and the flexibility of the platform, the size of these high power robots has been decreased below the minimum size required to dissipate the heat when known heat dissipation methods are used. To deal with such a problem, this paper presents the design and implementation of a special fully integrated cooling chamber developed to cool a fleet of approximately 100 of these instrumented robots without increasing their overall size while minimizing thermal drifts on the sensitive instruments through the use of an Helium atmosphere.

Keywords: Cooling chamber, Helium, miniature robots, nanotechnology, scanning tunneling microscope

1. INTRODUCTION

Although the concept of nanofactories has been introduced [1], the NanoWalker project [2, 3, 4] is the first example of a nanofactory based on a fleet of scientific instruments configured as wireless miniature robots designed for high throughput nanoscale operations. Although many instruments can be implemented, a miniature Scanning Tunneling Microscope (STM) [5] tip has been chosen initially to be mounted onto a special frame (Fig. 1) acting as the skeleton of the robot.

The STM relies on a four-quadrant piezoelectric tube with a tip at the lower end. When the tip is brought within approximately 1 nanometer (nm) from a sample or the surface, a tunneling current appears. This current provides feedback data that are used by an onboard processor to maintain the tip at specified distances from atoms at the surface. A post completes the current loop.

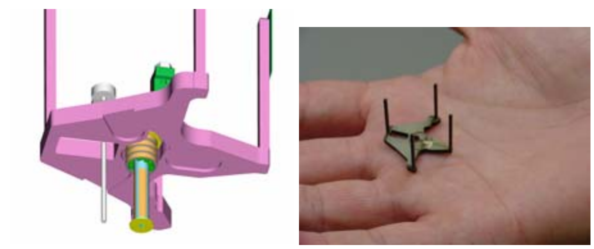

Figure 1. Representation of the STM tip encapsulated in the robot's skeleton with a photograph of the skeleton in a hand

By deflecting the piezo-tube, the current is maintained constant while the tip moves up and down during the scan. By tracking the position of the tip, an image can be reconstructed as depicted in Fig. 2. Beside imaging, STM can also be used for other more difficult tasks such as nanomanipulation and/or mechanosynthesis, i.e. using mechanical means to create new molecular structures.

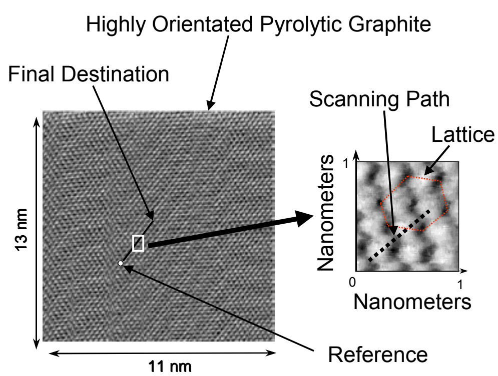

Figure 2. STM-based image

The instrument is mounted with legs made of piezo-ceramic. These legs allow each unit or robot to move on the platform. With a fleet of such instrumented robots [6], high flexibility and high throughput can be achieved but the complexity in controlling and managing such wireless system requires a fair amount of embedded electronics.

The embedded electronic system consists of a 12-layer flexible circuit mounted on top of the mechanical components as depicted in the Computer-Aided Design (CAD) representation in Fig. 3. As shown in Fig. 3, the flexible circuit can be bended to maintain the overall diameter of the robot to approximately 32 mm. Reducing the overall size is a critical aspect of the design since it allows more robots per surface area and hence, a higher throughput per platform for operations at the molecular and/or atomic scale.

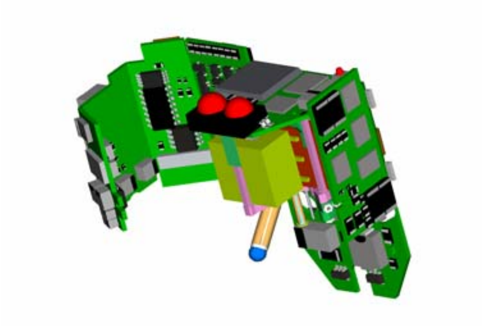

Figure 3. CAD representation showing the flexible circuit architecture

Fig. 4 and Fig. 5 show the final version of the NanoWalker robot. In Fig. 4, the STM is shown in the center surrounded by three piezo-legs used for displacement [7]. The power amplifiers are used to drive the tube scanner for the STM tip.

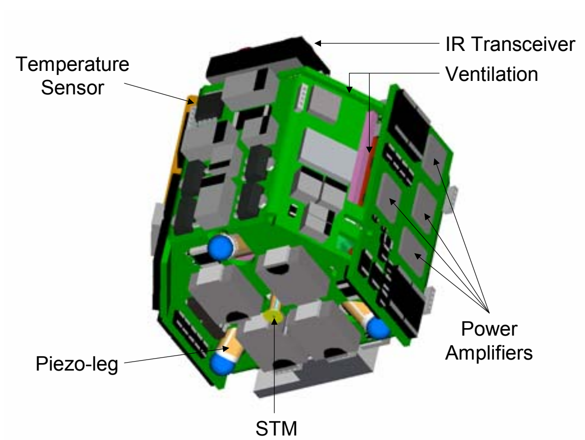

Figure 4. View from below the NanoWalker robot

Infrared (IR) transceivers operating in the 875-nm wavelength are used for communication between the robots and a central computer. Fig. 5 shows also two IR emitters or transmitters used for global positioning [8] (i.e. resolution of a few micrometers) while the STM tip is also used for atomic scale positioning (i.e. atomic resolution) using a special grid [9] made of Highly Oriented Pyrolytic Graphite (HOPG) with reference patterns engraved using a Focus Ion Beam (FIB).

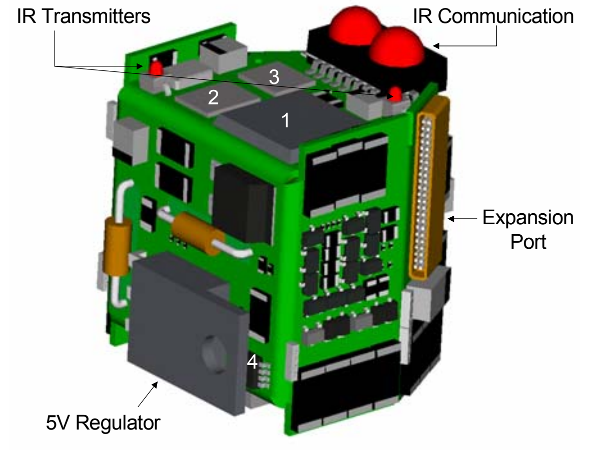

Figure 5. View of the NanoWalker robot

A photograph of the upper or outer side of the non-populated version of the flexible circuit is depicted in Fig. 6. In both Fig. 5 and Fig. 6, the components 1, 2, and 3 represent a custom controller, a Digital Signal Processor (DSP), and a memory device respectively.

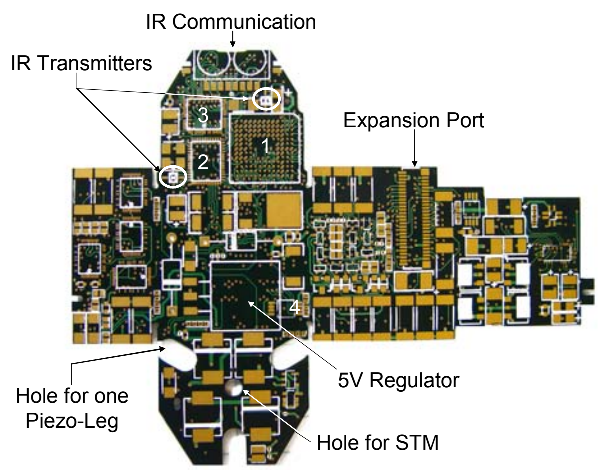

Figure. 6. Photograph of the bare board

One of the major issues in the miniaturization of such high performance instrumented robot is the heat dissipation. Estimations and preliminary tests showed that each robot dissipates between 15 and 20W of power on average. Although such issue can be easily resolved in larger systems, known solutions used in the electronic community such as heat sinks and/or heat pipes for instance, would increase substantially the size of each robot. The other approaches, e.g. [10] using wired microrobots in a Scanning Electron Microscope (SEM), teleoperation systems [11], or task-oriented closed-loop automatic control systems [12] using more conventional instrument architectures, avoid the problem of heat dissipation. This is done by embedding no electronics or only the low power instrumented electronics and related interfaces linked by wires to the high power electronics located at a remote site where miniaturization is not an issue. Although this approach is valuable for many applications, our proposed approach unlike other existing microrobotics and/or nanorobotics platforms, aims more specifically at increasing the throughput through a much larger number of miniature robots working simultaneously within the same platform. With this large number of robots, using wires that could be tangled and constraining the movements of the robots was not an option. Furthermore, past experiments [7] have shown that wires prevented repetitive step sizes in the nanometer range. The latency involved in communicating using wireless technology with an external computer in an attempt to reduce the amount of embedded electronics is far too long. This excessive delay prevents us to rely on an external computer for most of the real-time tasks (e.g. approximately 4,000 steps/s per robot during displacement, maximum of 200,000 measurements/s per robot at the atomic scale, etc.). It results that an average of 15 to 20W per robot was inevitable under these specifications. This is turn yields an average power dissipation between 1.5 and 2.0kW per platform, assuming 100 instrumented robots. This power is delivered through the legs of the robots when in contact with a special floor [13]. It is obvious that since no cooling methods were appropriate in our case, a new cooling method that will not affect significantly the size of the robots, while reducing possible thermal drifts on the sensitive instruments, was necessary.

2. COOLING PLATFORM

The main thermal problem of the robots is the ratio between the surface area and the power consumption of the electronic components. There are two fundamental approaches to solve this problem, mainly a reduction of the power consumption of the robot or an increase of the heat dissipation. Since the power consumption of the robot was already minimized, the heat dissipation had to be increased. This can be done either by enlarging the surface area of the robot or by applying external cooling. Within the space constraints imposed by the level of miniaturization, additional cooling fins or similar techniques used to increase the surface area were not sufficient. Altogether, this leads to the need of an external cooling system to protect the robots from overheating.

2.1 Mechanical vs. Chemical Refrigeration

There are different effects of heat and mass transfer to consider in such an implementation. This means conduction, convection and radiation. To dissipate the heat from inside the robot, conduction is mostly the issue. To dissipate the heat from the outer surface of the robots, there are two effects to consider: convection and radiation. In the present implementation, convection is a much more significant parameter than radiation.

Table 1. Mechanical versus chemical approaches

Parameter	Liquid Nitrogen	Mechanical
Capital cost of equipment	Low, approx. 25% of mech. system	High, especially for customized systems
Operating cost	Low, for intermittent systems, high for continuous operation	Relatively low for continuous operation, but not for intermittent
Maintenance	Nearly negligible	Low for normal refrigeration (temp.> -40°C), very high for temp.< -50°C
Space required	Compact, very efficient, uses less than 1/3 the space of equivalent mechanical system	Substantial space required, especially for a high volume production unit
Cooling rate	Extremely fast	Relatively slow
Minimum temperature capacity	Excellent, -185°C	Down to –70°C with a cascade system
Temperature control	Very good, PID or on/off	Very good, on/off only
Cooling medium	Nitrogen for direct cooling, any gas in indirect cooling	Usually air but almost any gas can be used
Vibration	Very low	High, from compressor
Effects on environment	Nitrogen gas has to be exhausted to environment	High heat load has to be dissipated

Convection can be categorized as natural convection and forced convection. Former calculations (not reported for the sake of brevity) show that natural convection alone is not sufficient to cool the robots efficiently. Therefore, a cooling system has to be designed that applies the effects of forced convection.

The technology used most often today is mechanical refrigeration. This means a cooling system consisting of compressor, chiller and various valves and pipes filled with refrigerant liquid. With a single loop system, it is possible to reach temperature of –40ºC. To achieve lower temperatures, a cascade cooling system consisting of two

loops arranged in a cascade is required. This type of system can provide temperatures down to –70ºC. Mechanical refrigeration systems are complicated but provide good control properties.
In comparison to that, a cooling system using the phase change between the liquid and the gas phase (or the solid and the gas phase) can be used. A common system uses liquid Nitrogen ejected by bleeding valves in an enclosure to freeze food rapidly. Table 1 summarizes some of the advantages and disadvantages of the two approaches. The low vibration requirement coped with a fast cooling rate and the lower achievable temperature forced us to select a cooling system with Helium indirectly cooled with liquid Nitrogen.

2.2 General Description

A diagram of the cooling platform under development is depicted in Fig. 7.

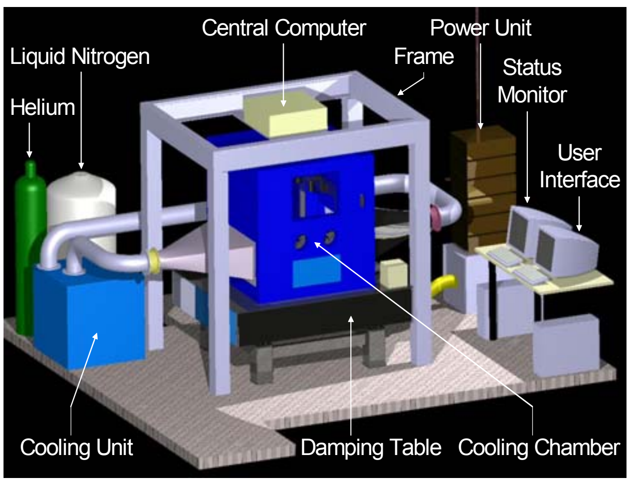

Figure 7. CAD representation of the cooling platform

The system is comprised of a cooling chamber filled with Helium gas, a cooling unit, and a vibration damping system. The transition of liquid Nitrogen to a gas state is being used to cool Helium gas flowing through a coil in a cooling unit. Helium is used because it is an inert gas, which is suitable in many operations performed at the molecular scale. Furthermore, Helium is not flammable and very safe. Since Helium is a very good heat conductor, it helps minimizing the flow, which in turn minimize possible thermal drifts on the sensitive STM.
The size of the cooling chamber has been designed to accept at least 100 NanoWalker robots, offering the capability for more than 20×10^6 STM-based measurements/s per platform. Beside the surface area with dimensions not exceeding 0.8m × 0.8m required to place and maneuver the robots, the internal height of the cooling chamber is determined in great part by the distance between the global positioning system and the powerfloor (Fig. 8). For optimal performance, this distance is estimated at 777.58 mm between the IR emitters on top of the robots and each Position Sensing Device (PSD) or unit.

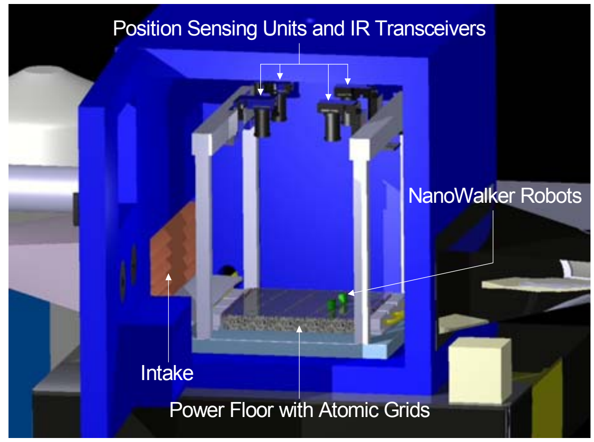

Figure 8. Inside the cooling chamber

The global positioning system is based on four PSDs. Each PSD is mounted with an IR transceiver providing four independent cells of 330mm in diameter on the walking surface for communication and positioning. Because of the limited vertical distance of the IR communication at full throughput and the line of sight of the IR emitters and transceivers, four PSDs offer the best approach to support a fleet of at least 100 NanoWalkers. The PSDs provide sufficient resolution to within a few micrometers to position each robot within an atomic grid. Once located within a specific grid, a special scanning mode using the embedded STM allows for atomic resolution positioning. After several iterations, it was concluded that the robots and all the PSDs should be within the same cooling chamber since it was critical to provide a line of sight free of obstructions that could potentially cause distortions that would affect significantly the resolution of the system.

Figure 9. Photograph of the cooling chamber

3. SPECIFICATIONS

The cooling chamber is shown in Fig. 9 and the specifications of the cooling system are summarized in Table 2. The specifications are for a platform supporting 100 NanoWalker robots. The system is also designed to maintain the internal temperature of each robot between 0 and 70ºC.

Table 2. Specifications

Standard Equipment (Chamber)	
Internal dim. External dim. (W×H×D)	1300×1200×1200mm 1500×1400×1400mm
Interior finish Exterior finish	Stainless steel #4 Epoxy coated mild steel
Insulation type	Foamed-in-place polyurethane
Window Arm ports Airlock (W×H×D)	600×400mm with shade 2×222mm diameter with butyl gloves 260×165×250 mm Airlock fitted with a purge valve to reduce intake of air
Inlet and Outlet He diffusers	700×400×600mm (W×H×D) Adjustable fins on inlet diffuser and filter mount on outlet diffuser
Mounting	Flat rubber mount pad
Illumination	Built-in fluorescent
Primary elect. connection	120VA/60 Hz/1-phase/15A
He connection Vent outlet Vacuum breaker	12.7 mm tube 12.7 – 50.8 mm Included
Cable Ports	Top 2×140mm diameter Back 2×140mm diameter
Cooling System (Remote)	
Type	Remote liquid Nitrogen exchanger
Connections	9.5 mm LN_2 / 50.8 mm NPT vent
Capacity	4.4 kW
Min. temp.	-185 °C
Ventilation	Fan forced, max. 3.4 m^3/min
Ducting	101.6mm diameter, insulated
Special note	System insulated from chamber to eliminate vibrations
Dimensions	400×457×343 mm (W×H×D)
Other features	Built-in 120VA/ 60 Hz/ single ph. Built-in cryogen injection for liquid N_2 including manual isolation valve, automatic injection valve and necessary relief valves

Instrumentation

Parameter	Range	Res.	Sensor type
Temp.	-200 °C - +200 °C	0.1 °C	T-Type thermocouple
Pressure	0-1245.4 Pa	2.5 Pa	Piezoresistive strain gage diaphragm (differential)
Humidity	0 – 100 % RH	1 %	Capacitive film
Air flow	0 – 3.4 m^3/min	0.028 m^3/min	Variable frequency controlled fan

Control & Alarms	
Temperature	Feedback with programmable heat/cool ramp rates; high/low alarm indication
Pressure	Internal atmospheric pressure indication; high/low alarm indication
Humidity	Internal atmosphere humidity indication; high/low alarm indication
Oxygen	Internal atmospheric oxygen concentration indication; high/low alarm indication
Interface	
External interface through RS-232C or RS-485 communication (temperature set point can be remotely adjusted via computer)	
Performance	
Cool down rate at maximum load (1500 Watts) LN_2 consumption	Minimum of 7.5 minutes from 20 °C to -70 °C at start up conditions Approx. 12 kg/h at maximum heat load and steady state conditions

The internal temperature level is provided by each robot to the main computer through the IR communication link. Three electronic temperature sensors embedded in each robot are used to gather temperature levels at strategic locations. Based on the temperature levels of each robot, an algorithm is used to adjust the chamber temperature at the minimum possible rate in order to avoid fast and unpredictable thermal drifts on the sensitive instruments.

4. SUMMARY

A new cooling system for scientific instruments configured as miniature robots capable of operations at the atomic scale has been described. The design of such system must take into consideration various constraints and requirements specific operations at such a scale, such as vibration and temperature fluctuations which have to be minimized to allow a stable distance between the tip of the STM and the sample. The chamber has been designed taking into account further necessary developments, such as air flow adjustment and automated robot control and organization to optimize the heat drain from all the 100 units. To do so, special cable ports have been designed to allow sensors signals and computer feedback from an external unit. Such a platform and the specifications have been provided.

5. ACKNOWLEDGEMENT

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