Cooling Strategies for High Performance Miniature Wireless Robots Designed to Operate at the Nanoscale

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***Abstract*—The concept of high throughput nanorobotics platforms based on a fleet of miniature wireless robots capable of fast operations at the nanoscale offers many advantages compared to other approaches. But as the size of these instrumented robots decreases with a potential increase in performance, the surface available on each miniature robot to dissipate the heat becomes insufficient. Since known traditional methods of heat dissipation cannot be applied, other cooling methods better appropriate within the constraints of such nanorobotics platforms must be considered. Two novel cooling strategies for high performance miniature robots designed for nanoscale operations are proposed. One method exploits the heat capacity of water in a special thin multi-layer jacket installed on each robot. Another method places all robots in a Helium atmosphere cooled with liquid Nitrogen.**

Keywords-cooling; nanorobotics; miniature wireless robots; heat dissipation; water evaporation; Helium

I. INTRODUCTION

Miniature wireless robots designed to operate at the nanoscale may play an important role in nanotechnology [1]. For instance, although arrays of scanning tunneling microscope (STM) [2] or atomic force microscope (AFM) tips or other instruments used in nanotechnology can be used to increase throughput, many applications would require independent control and/or location of a single tip or an array of tips. Hence, a potential system's architecture would be based on independent instrumentation modules, each with one or an array of instruments. In a more traditional system's architecture, these instrumentation modules would be implemented following a model similar to other high throughput robotics manufacturing and pharmaceutical infrastructures, i.e. using a pipeline approach. This approach is well suited for high throughput applications when the tasks can be divided as sub-tasks with equal execution time. At the nanometer-scale, this means applications with no or negligible execution time uncertainties. For applications where the execution time of one or more sub-tasks in the pipeline cannot be predicted with enough accuracy, loss in the overall performance of the pipeline is likely to occur due to waiting time for one or more sub-tasks to complete. Hence, when time uncertainties exist in the execution of a sub-task, it is suitable to have a system's architecture where such time uncertainties will not have a negative effect on the overall throughput of the platform.

This suggests the use of modules capable of independent displacements. To this end, there are two fundamental approaches that can be pursued, either the modules carry the samples to the instruments or the instruments are brought to the samples. In both cases, power circuits, precise displacement capability, atomic-scale positioning, embedded computation, and communication must be supported. But embedding the instrument provides a miniature wireless instrumentation module having a higher resonant frequency and therefore, makes each module less sensitive to a larger frequency band of external vibrations. Nonetheless, even if some of the tasks can be performed by an external computer and data communicated via a communication channel, many tasks need to be executed by the electronics embedded onto each module because of the too long communication and processing latency between each instrumentation module and an external computer. Miniaturization is a key concept here since it allows a higher density of instrumentation modules per surface area leading to higher throughput of the platform. With a high level of miniaturization, the result is a relatively high performance instrumentation module that cannot dissipates the heat efficiently due to the relatively small surface area available.

II. INSTRUMENTATION MODULE

To fulfill the requirements for such nanorobotics platforms, the proposed instrumentation module has the form of a miniature wireless robot as depicted in the computer-aided design (CAD) representation shown in Fig. 1. It consists essentially of a mechanical frame with a locomotion system, an embedded instrument, and power converters covered by an electronic system in the form of a 12-layer 0.5mm thick flexible circuit designed to provide the minimum required embedded functionality. The embedded electronics has a 48 MIPS digital signal processing (DSP) system with memory, an instrumentation interface with 200 KS/s 16-bit A/D conversion,

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drive electronics for the piezo-actuators and scanning system, additional power conversions and regulations, 4 Mbps half-duplex infrared communication, and several other sub-systems. Although this version called NanoWalker [3] has an embedded STM, other instruments or an array of instruments could potentially be integrated in the future.

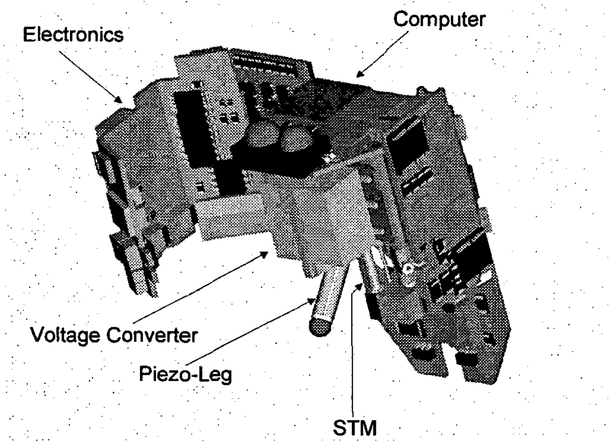

Figure 1. Instrumented miniature robot with electronic module unfolded.

For accurate locomotion, the NanoWalker relies on three piezo-legs (one is visible in Fig. 1) made of three piezo-ceramic tubes mounted as a conical shape with the apex pointing upward. Piezo-actuators provide small deflection amplitudes required for accurate displacements with a high resonant frequency. Since no useful work is being done when to robot moves to the next destination, high resonant frequencies translate in our case to several thousands of steps executed by the robot per second with step sizes varying from a few tenths of nanometers to a few micrometers. A major drawback of using piezo-actuators is the high actuation voltage required for full deflection amplitude. Other option such as using a bimorph design is not suitable here since the piezo-legs must provide maximum force for adequate motion. In our particular case, actuation signals with maximum amplitude of 300 Volts (±150V) are used. Three legs provide static stability of the structure and minimize the amount of drive electronics and related power dissipation.

The amplitude modulation used in piezo-drive electronics typically requires a D/A converter and a power amplifier per quadrant electrode on each piezo-leg. The quiescent current alone for the additional 12 power amplifiers would increase the maximum DC load of the voltage converters (the 5-150V DC/DC converters) by an additional 24mA at ±150VDC. Considering that two 5-150V DC/DC converters can be used to drive the STM scanning tube and the piezo-legs in a time multiplex fashion, using amplitude modulation to drive the piezo-legs would require four additional 5-150V DC/DC converters. Knowing that each of these 1.25W 5-150V DC/DC converters has dimensions of 12.7mm x 12.7mm x 8.64mm and that the overall dimensions of the robot with two 5-150V DC/DC converters are approximately 32mm x 32mm x 30mm, it is obvious that the added DC/DC converters would increase the overall dimensions of the instrumented robot significantly. Furthermore, with approximately 80% power conversion efficiency, the additional four DC/DC converters alone (without accounting for the power dissipation of other components such as the additional 12 power amplifiers) would generate an additional 1W of power dissipated as heat. In the design depicted in Fig. 1, these additional DC/DC converters and power amplifiers have been avoided by frequency-modulate the actuation signals at the resonant frequency of the piezo-legs. Smaller deflection amplitudes are achieved by frequency modulations beyond the resonant frequency of the piezo-actuators.

Although the new modulation scheme allows further miniaturization and a significant reduction in the amount of heat generated, the power conversion alone still generate a fair amount of heat. A basic block diagram of the power conversion system embedded onto each instrumented robot is depicted in Fig. 2.

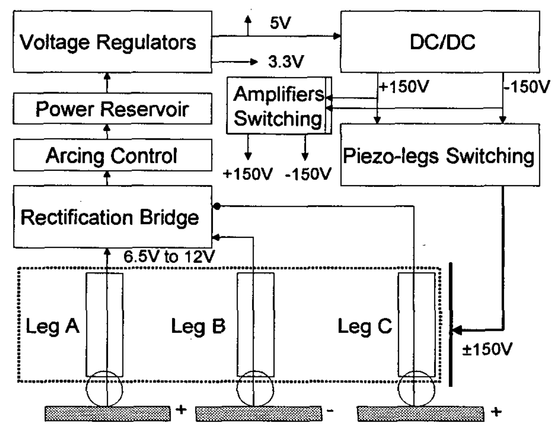

Figure 2. Power conversion scheme.

As depicted in Fig. 2, because no technology with adequate energy and power density exists, power is presently provided through the piezo-legs of the robot when in contact with special positive and negative power bands on the surface [4]. The dimensions of the power bands are chosen to guarantee that at least one leg could be in contact with a positive band and at least another leg could be in contact with a negative band. Such surface or power floor typically provides power as a DC voltage between 6.5V up to approximately 12V which appears at the input of a 5VDC voltage regulator. With an average electrical current of approximately 1.5A, the minimum acceptable voltage of 6.5V required to guarantee proper voltage regulation, already generate 2.25W of power dissipated as heat through the 5VDC regulator alone. But since the legs are not in contact continuously with the surface when executing each step, a small power reservoir in the form of a capacitor is used as a limited energy source to complete each step. Because of the exponential discharge rate of the capacitor, higher input voltage would provide more flexibility and time to complete each step when in motion but at the cost of additional heat. At least another half a Watt is also dissipated as heat through the 3.3V regulator. One ±15V DC/DC converter (not shown in Fig. 2) required for the analog electronics dissipate approximately 200mW at full load, whereas the two 5-150V DC/DC converters generate approximately 0.5 Watt of heat. In the power conversion scheme shown in Fig. 2, most heat is dissipated as static power dissipation except for the 500mW of power dissipation of the 5-150V DC/DC converters, which is dissipated mostly as static power dissipation when in instrumentation mode only due mainly to the quiescent current flowing through the power amplifiers used to drive the scanning tube of the STM. Heat is then dissipated in great part as dynamic power dissipation when in walking or displacement mode and is dependent on the modulation frequency. The amplifiers switching block depicted in Fig. 2 is used to switch between the instrumentation and the displacement modes. The arcing control block also depicted in Fig. 2 is used to prevent arcing during each step which otherwise would cause erosion on the surface and the extremities of the legs, making repetitive accurate step sizes very difficult. Previous experiments with all electronics embedded onto the robot and 6.5VDC at the input showed an overall power dissipation in the order of 15-20W. It is therefore interesting to note that in the best case, the power conversion alone accounts for approximately 20% (3W) of the whole power dissipation but that if the input voltage increases from 6.5VDC to 12VDC to allow for more time and flexibility to execute each step during displacement, the power conversion system depicted in Fig. 2 becomes much less efficient with an increase of heat dissipation from approximately 3W to 11W.

III. Heat Disspation Methods

It is very difficult to dissipate heat without increasing significantly the overall size of the robot. For instance, common heat dissipation methods for high-speed and high-powered electronics include heat sink attachment and forced convection cooling. The use if a heat sink would increase the overall size of the robot significantly. Smaller heat sinks could be used with higher forced convection cooling. Forced convection cooling with a fan integrated onto the robot would cause inertia that would impede step size accuracy, especially if a smaller heat sink is achieved through a higher flow rate. The flow rate through an external forced convection system needs to be minimized as well to avoid excessive thermal drifts on the sensitive instruments and to minimize the impacts on the motion of the robots and minimize turbulences caused by neighbored robots.

A. *Liquid Boiling Convection*

Much like free air convection, liquid boiling convection is driven by temperature potential and it is proportional to the surface area exposed to the liquid. But unlike free air convection, liquid boiling convection has the highest heat transfer rate for a given surface area and it is mainly due to the power or energy required (latent heat) for the liquid to gas transition. A large amount of energy is also required to the liquid from its initial temperature up to its boiling point and which is proportional to the fluid specific heat and the change in temperature the fluid experiences. The total amount of energy transferred to the fluid, which must be maximized for smaller high performance robots, can be computed as

$$E = m\,[h + c\,(T_b - T_i)]. \quad (1)$$

In Eq. 1, E is the total amount of energy transferred, m is the mass of the fluid, h is the latent heat of the fluid, T_b and T_i are the boiling and the initial temperature of the fluid respectively. Water and in our case distilled water is usually the ideal liquid for heat transfer applications because of its very high latent heat (2.5 MJ/kg) and specific heat (4.2 kJ/kg K) [5].

Another concern is that the surface of the miniature robot is a dense layer of electric and electronic components with different power dissipations. For instance, each of the 4 power amplifiers used to drive the scanning tube for the embedded STM tip, dissipates 0.8W in a surface area of only $19\text{x}10^6\ m^2$. Hence, good heat conductivity or heat flux becomes critical to spread the heat as evenly as possible over the whole surface.

The proposed thermal structure or jacket wrapped over the flexible electronic system of each robot is designed to maximize the volume of water it can contain while keeping its overall thickness to a minimum. The present version of the thermal jacket consists of 8 layers of porous material sheets with very high water capacity and capillary characteristics, encapsulated between two thin copper sheets with a thin layer of ceramic and insulated thermal compound between the electronics and the first copper sheet. Capillarity is critical to attract water to the hottest regions. Past experiments have shown that without good capillary effects, the hottest regions became dry while water was still remained in other sections of the thermal jacket. The inner copper sheet helps in heat spreading while the outer copper sheet provide additional surface for free air convection. The ceramic compound provides relatively good heat spreading and unlike the copper plates, it provides electrical insulation. A small gap is provided on the top of the jacket to allow evaporation and for refills. With an overall thickness of 1.22mm, the actual version of the thermal jacket contains approximately 0.6 grams of water per refill. This is sufficient to extend the operations of the robot from a few seconds to a few minutes (approximately 3 minutes of continuous operations at 13.5W with temperature of the water initially set to room temperature). Experimental results are shown in Fig. 3 with refills showed as vertical lines.

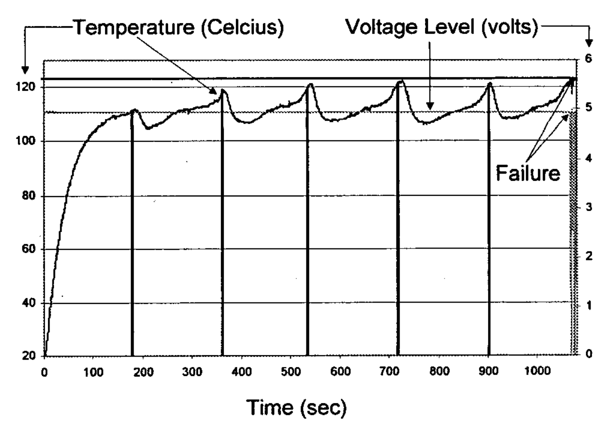

Figure 3. Experimental data for the 1.22mm thick water boiling convection jacket at 13.5W power dissipation with 0.6 gram refill every 3 minutes.

As shown in Fig. 3, by delaying the filling process, the 5VDC voltage regulator failed due to rise of temperature beyond the maximum junction or case temperature, causing a global failure the whole embedded electronics. This approach has several important drawbacks. For instance, the maximum operating temperature for the 5VDC regulator in the small package decreases with an increase of power dissipation. For instance, at the boiling temperature of water, the maximum power dissipation is approximately 18W. This suggests that beyond 18W, larger components must be used and/or water-based liquid boiling convection is not an option anymore. Another limit is that the maximum operating temperature of many electronic components is 70°C, and therefore must be cooled differently, ideally by free air convection through an independent heat sink. Another disadvantage of this approach is the refill process, which may become problematic if a large percentage of robots in a relatively large fleet need a refill at the same time. The refill system may also impede tasks such as optical positioning and wireless communication by blocking lines of sight and therefore, reducing the available bandwidth. Another potential problem is that with the present version, the weight of each robot would vary by ~1.5-2%.

B. Helium Atmosphere

Helium is an inert gas with 4.8 times the heat conductivity of air. This means that during forced cooling, the flow rate of Helium can be minimized compared. The reduction in the flow rate decreases thermal drifts on the sensitive instruments, motion errors of the robots, and turbulences caused by neighbored robots. Furthermore, when operations at the nanoscale can be done at very low temperature levels, the flow rate of Helium can be reduced further through a cooling process. A single-loop mechanical cooling system can reach temperature level of -40°C and down to -70°C in a cascade system consisting of two loops. Mechanical refrigeration systems can cause substantial vibrations through the compressors to the nanorobotics platform. In our case, a cooling platform [6] using the energy of the phase between liquid Nitrogen to a gas state to cool Helium gas flowing through a special coil was developed. The system allows temperature levels well below the temperature levels achievable with a mechanical system with much less vibration.

In order to keep track of the temperature levels, three programmable electronic temperature sensors have been embedded onto each robot at strategic locations. When the temperature level of one sensor reaches an upper- or lower-bounded temperature level set to guarantee proper operations of the unit, an interrupt is generated to the onboard processor. A message is transmitted from the robot to the central computer through the infrared wireless communication link. The central computer then interrogates each miniature robots through the same infrared communication link to obtain a temperature profile of the whole fleet and the temperature of the Helium gas is adjusted appropriately. Since the whole platform is cooled at the same level, it is important to minimize variation in the temperature levels not only among the miniature robots but also within the each robot. Therefore, the use of a miniature heat sink designed to provide sufficient heat spreading throughout the surface of each robot is very critical. The position of each robot may also be an important factor that contribute to increase the variation in temperature among robots, for instance when a robot is blocking the direct laminar flow of Helium to another robot. Hence, particular attention must be paid on the locations of each working zones to maintain variations in temperature to an acceptable level that can be centrally controlled. Helium has several properties suited for many nanometer-scale applications. Being an inert gas, reaction at the molecular scale is avoided. Furthermore, Helium avoids corrosion and/or oxidation that would make accurate repetitive motion of the robots more difficult. But the dielectric of Helium increases substantially the risks of arcing, especially with smaller geometries and high voltage levels.

IV. CONCLUSIONS

A platform having a fleet of instrumented robots capable of nanometer-scale operations and independent displacement capability has been proposed. As the size of these robots decreases, the surface available to dissipate the heat becomes insufficient. Relying on an external computer to decrease the amount of embedded electronics is not a viable option due to the too long latencies. Conventional heat dissipation techniques cannot be applied since it would increase substantially the size of each robot. As such, two novel heat dissipation approaches are proposed. One is based on water boiling convection where a thin multi-layer jacket is installed on each robot. This approach involves small variation in the overall weight of the robot and limitations in the temperature level that can be maintained. Another approach uses a Helium atmosphere cooled with Nitrogen. The high heat conductivity of Helium allows us to reduce the flow rate for forced convection cooling, hence minimizing thermal drifts and turbulences. Helium has many good characteristics but arcing becomes a real issue with further miniaturization.

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