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Micro- and Nano-Scale Robotics

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Abstract—**Micro- and nano-scale robotics has become a new emerging area of systems and controls area recently. These miniature robots have unique advantages such as accessing to unprecedented and small areas, increased flexibility, functionality and robustness, and being low cost, many (swarms), adaptive and distributed. The locomotion and manipulation dynamics of these robots are dominated by micro/nano-scale forces and the scaling effects. The long term target is the miniaturization of these robots down to micrometers size. However, currently, these robots have sizes from tens of centimeters down to millimeters due to limited miniaturization and integration capabilities of available power sources, communication, control and computation schemes and tools, and coarse to fine motion mechanisms, sensors, manipulators, and actuators. This tutorial addresses the research challenges and future directions for these robots with many case studies such as Scanning Probe Microscope dynamics and control, nano-scale manipulation and assembly, human-machine interfacing, and miniature surgical micro/nano-robots.**

I. INTRODUCTION

MICRO and nano-scale systems have been one of the new frontiers of systems and control research field. Thus, robotics at these scales has been also emerging as a new area. These robots would enable new tools and novel approaches to design, construct, and control micro- and nano-scale systems. A micro/nano-robot with overall sizes from macro-scale to millimeter and sub-millimeter range can be defined as a robotic system that can realize programmed tasks at the micro/nano-scale. These miniature robots have unique advantages such as accessing to unprecedented and small areas, increased flexibility, functionality and robustness, and being low cost, many (swarms), adaptive and distributed. The locomotion and manipulation dynamics of these robots are dominated by micro/nano-scale forces and the scaling effects. The long term target is the miniaturization of these robots down to micrometers size (such as cells as the smallest micro-machines in nature). However, currently, these robots have sizes from tens of centimeters down to millimeters due to limited miniaturization and integration capabilities of available power sources, communication, control and computation schemes and tools, and coarse to fine motion mechanisms, sensors, manipulators, and actuators.

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This paper defines the research problems and directions of micro- and nano-scale systems with a basic introductory background and many case studies. These studies include Scanning Probe Microscope dynamics and control, nano-manipulation and nano-assembly systems using robotic and directed self-assembly approaches, human-machine interfacing, and miniature micro/nano-robots.

II. BACKGROUND ON NANO-SCALE SYSTEMS, DYNAMICS AND CONTROL

Scaling a soccer ball down to a nano-particle size, surface to volume ratio increases inversely proportional to the length scaling factor, and therefore, surface properties and forces start to dominate bulk properties and forces. This fact is mainly called as the scaling effect. Thus, the dynamics of a nano-particle are much different from a soccer ball such that the nano-particle dynamics are dominated mainly by drag, frictional, and spring forces while nonlinear and attractive or repulsive external nano-forces pull or push the particle through a long- or short-range effect. These nano-forces are intermolecular forces such as van der Waals, Casimir, capillary, hydrogen bonding, covalent bonding, Brownian motion, steric, hydrophobic, double layer, etc. forces which we neglect at larger scales. These forces have following basic common properties:

- They are nonlinear, i.e. mostly function of r^{-n} ($n \geq 1$), where r is the distance between two nano entities. Thus, close to interatomic distances, these forces increase drastically.
- They can be long-range or short-range, and attractive or repulsive.
- They are very sensitive to the environmental parameters such as temperature, humidity, surface chemistry, contamination, and mechanical and electrical noises.
- They depend on the nano-entity geometry and size.
- They depend on the entity material type. For example, Casimir forces exist only for conductive materials. Here, analogous to the gravity at the macro-scale, van der Waals forces are the *only* forces existing for any material type in any environment.
- Some of these forces become dominant only in specific environments such as air, liquid or vacuum. For example, for neutral and non-magnetic entities, van der Waals, capillary and electrostatic forces mainly dominate in air, while in liquids, capillary and

electrostatic forces do not exist, and van der Waals, double-layer, hydrophobic, steric, ionic, etc. type of other forces become dominant depending on the liquid pH, ionic concentration, material ζ-potential, hydrophobicity, etc.

Due to the above properties, the *specificity* of tasks increases exponentially at the nano-scale: depending on the dominant intermolecular forces, geometric, chemical and physical surface properties, and possible environmental conditions and disturbances, tasks are required to be defined and designed more specifically. On the other hand, the functional *complexity* of the systems increases due to the above nonlinearities and precision and functional requirements for sensors, actuators, and tasks increase exponentially at the nano-scale. Therefore, designing robust and stable controllers for nano-scale systems to achieve a specific task becomes very challenging. There are many constraints exerted on the controller design and performance by the time-varying nonlinear system dynamics, system parameter uncertainties and changes, short dynamic time-scales, disturbances from the environment, sensitivity to the changes in system parameters, limited sensor information, limited actuator motion precision and range, and limited power issues. Here, on-line system identification methods and adaptive and self-tuning controllers specific to the nano-scale systems become very attractive for a high performance and autonomous control.

As another significant scaling effect, nano-scale mechanisms have faster dynamics. Thus, the time-scales can become very short down to pico- and femto-seconds. For example, controlling a nano-scale resonator with MHz or GHz resonant frequency in real-time is a new future challenge for the controls community. Here, it is almost not possible to have a closed-loop control using conventional computer or DSP based control hardware due to the MHz or GHz range of bandwidth requirements. One possible revolutionary solution would be using nano-electromechanical structures with integrated sensors and actuators as an *in-situ* closed-loop controller. Thus, we might need to go back to the roots of the mechanical process control concept in ancient times such as the centrifugal speed governor. It consists of a couple of steel balls attached to a vertical rotating shaft. Two further links connect the balls to a sliding collar on the shaft, which in turn is linked to a vertical rod which leads to the valve controlling the steam input to the engine. As the engine speeds up, centrifugal force causes the balls to move outwards which in turn moves the rod and reduces the steam input to the engine. Thus an equilibrium point is reached at which the engine settles down to a more-or-less constant speed.

Since the nano-scale mechanics and dynamics are not completely understood yet, *modeling* nano-scale interactions is very crucial. Quantum electromechanical models enable detailed and accurate modeling of specific nano-scale interactions. However, they are computationally intensive, limited currently to special materials and cases, and difficult to scale up. The second approach is to use the Molecular Dynamics and Monte Carlo type of intermolecular models. These models give close to accurate results although they are very slow and not able to model multi-time and multi-length scale phenomena effectively yet. The final approach is to approximate the nano-scale dynamics using continuum physical models. Main advantages of these models are their computational speed and easy scaling capability. However, there are still wide range of materials, geometries and environments for which there exist no realistic continuum nano-simulator tools.

III. Scanning Probe Microscope (SPM) Dynamics and Controls

SPM dynamics and controls is one of the first and most studied research directions of the nano-scale DSC community due to the increased demand of the SPM companies to improve current SPM control, signal processing, system identification, and imaging/sensing science and technology, and similarity of the SPM dynamics, control and modeling to many widely studied mass-spring-damper system problems with external and internal dynamic nonlinearities.

The Atomic Force Microscope (AFM), as one of the subclasses of SPMs, since its invention by Gerd Binnig and

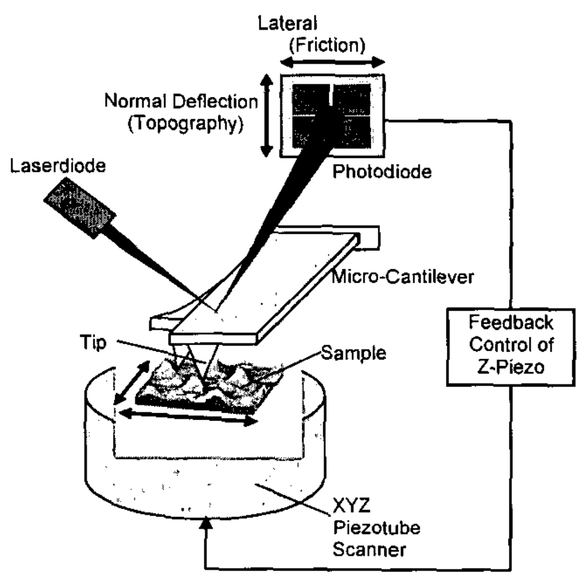

Figure 1 Basic setup of an atomic force microscope (AFM)

Christoph Gerber in 1985, has had a deep impact in many areas of science and technology. AFM is used to image surfaces with remarkable resolution down to molecular scale. The operational idea of this tool is to detect the displacements of a micro-cantilever tip as the sample surface moves under it. A typical AFM consists of a micro-cantilever probe, a sample positioner, a detection system for measuring the cantilever deflections, and a control system for maintaining a desired contact force as shown in Figure 1. It is a device used to investigate and manipulate materials in nano and atomic scales. This investigation includes a wide range of materials which includes thin and thick film coatings, ceramics, composites, glasses, synthetic and biological membranes, metals, polymers, and semiconductors. This device is used to study a variety of phenomena such as abrasion, adhesion, cleaning, corrosion, etching, friction, lubrication, plating, and polishing. Consequently, AFM has revolutionized basic research in sciences such as in biology, chemistry, material science and tribology, and has greatly affected technologies such as electronics, telecommunications, biotechnology, materials, and computer industries.

Recently, there has been a growing interest in Atomic Force Microscopy in the control systems community as described in [1]. Their contribution has been in analysis, modeling, and improving device performance. System and dynamic systems concepts have also been used in studying micro-cantilevers and analyzing their interactions with sample surfaces. System tools have been used to study steady state behaviors of cantilevers, explain rich complex behavior observed in experiments, and derive fundamental limitations on this technology. The system identification techniques have been used to provide mathematical models of the system without the need to deal with the complex geometry or material composition of the device. The fine resolution and large range of motion for these devices are typically provided by piezoelectric actuators. However, piezo-actuation introduces effects such as hysteresis, drift and creep which adversely affect the performance of the device. System tools have been applied to study these effects and compensate for them. The PID control, which is typically employed for control in these devices, is inadequate in many cases to realize their full potential. Consequently, robust control tools have been proposed and implemented which have shown substantial improvement in simultaneously achieving fine resolution, high bandwidth and robustness of these devices. The need for high throughputs in many applications has imposed severe demands on these devices. Several system theoretic methods are being applied to address this need, for e.g., increasing the detection bandwidth using observer based control scheme and increasing the throughput by implementing an array of cantilevers by using analysis and

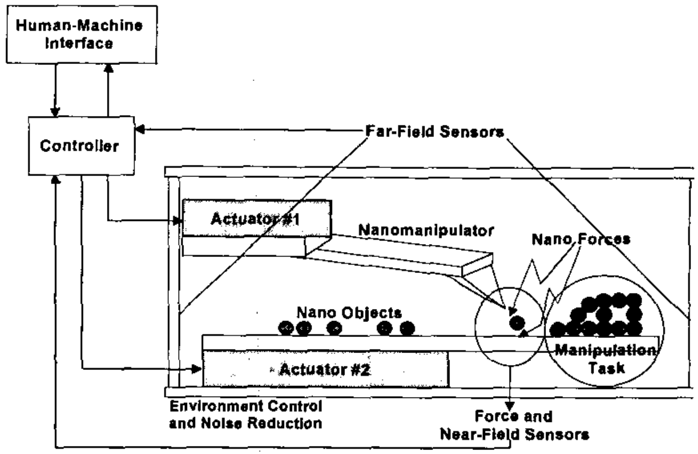

Figure 2 A generic robotic nano-manipulation system setup

control tools from the area of distributed control theory.

Adhesion (van der Waals), nano-scale impact, liquid bridge, electrostatic, and double layer forces are inherently nonlinear for AFMs in the sense that their magnitudes vary nonlinearly with distance. Analyzing and understanding the nonlinear dynamics of AFMs is critical for the development of high-speed stable AFM imaging and novel sensing techniques, and can help design faster, more stable scanning probe systems, probe based lithography and data storage devices, and can help understand atomic scale dissipation and friction.

As future research directions and challenges, a new generation self-tuning and autonomous AFMs are to be developed. Most current AFM PID scanning control parameters are tuned manually by a user based on trial and error. Furthermore, the current controllers mainly use the probe deflection, amplitude, and the fundamental resonant frequency as the control parameter. Using harmonic frequencies, phase, etc. type of new control parameters, novel imaging methods would be introduced. Here, the control and system parameters would be tuned and identified automatically for optimized scanning of any unknown surface material and complicated three-dimensional (3-D) topography. Moreover, instead of PID type of linear controllers, nonlinear and self-learning control algorithms should be developed for adaptive, robust, stable, and fast scanning. Finally, a realistic nano-simulator using continuum or molecular nano-physical models of an AFM probe tip and a surface interaction in any environment (air, liquid, and vacuum) should be developed for improved understanding and simulated design of novel control algorithms. The simulator model parameters should be tuned by comparing with controlled AFM nano-force measurements.

IV. NANO-MANIPULATION AND NANO-ASSEMBLY

One of the targets of nanotechnology is to control matter

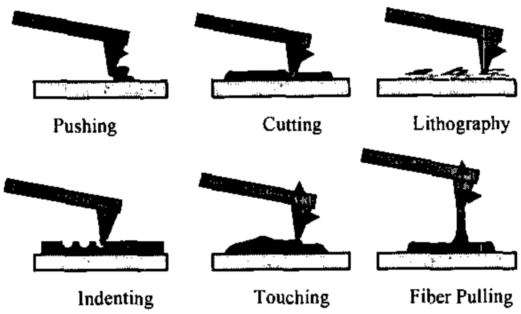

Figure 3 Example mechanical nano-manipulation tasks using an AFM probe

and nano-scale entities precisely for forming specific functional materials, devices and systems. One method for obtaining this precision is the manipulation of nano-entities using nano-scale manipulation tools or directed self-assembly. Precise manipulation can be defined as positioning, assembling, cutting, pushing/pulling, indenting, scratching, twisting, grabbing, releasing, injecting, or any type of interaction which would change the relative position and relation of entities through direct or indirect human operator control. Moreover, the ability to assemble multiple micro- and nanometer sized components in two or three dimensions will enable the creation of new devices and systems with new functions or increased performance.

Nano-manipulation has been the most studied nano-scale dynamics, systems, and controls research topic since the beginning of the 1990s. The first revolutionary example was Eigler et al.'s [2] atomic manipulation demonstration of Xenon atoms in 1990 in almost absolute zero temperature conditions. This experiment showed the possibility of positioning individual atoms precisely using electrical pulses applied by a Scanning Tunneling Microscope (STM) probe tip.

Nano-scale manipulation and assembly approaches can be classified generally as *robotic* and *directed self-assembly* based approaches. In the former, a nano-robotic tool applies a physical force such as mechanical contact,

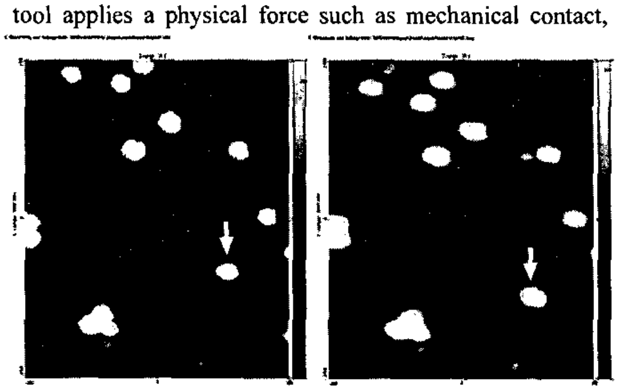

Figure 4 Using an AFM probe to push a 28 nm diameter gold nano-particle deposited on mica using poly-L-lysine (image scan size: 500 nm x 500 nm) [7]

laser light pressure, electrical gradient, etc. on entities to precisely locate and interact with them. A generic robotic nano-manipulation system is shown in Figure 2. This is mostly a top-down approach to manipulate smaller and smaller entities with higher and higher precision. On the other hand, the latter approach is bottom-up, and directs self-assembly and self-organization process to build controlled structures and devices. Both approaches are described in more detail below.

A. Nanorobotic Manipulation

As the most common robotic nano-manipulation tool, a sharp AFM probe tip is used to push, pull, cut, and indent materials and surfaces as illustrated in Figure 3 in addition to its designed imaging uses. The main advantage of using the AFM as a nano-manipulator is its capability of sense force and image 3-D topography. Many groups [3-5] showed 2-D precise positioning of nano-particles on surfaces using contact pushing. An example pushed gold nano-particle is displayed in Figure 4. The main strategy is as follows: (1) Image the surface with semi-fixed nano-particles using AFM tapping mode imaging for minimal distortion on the particle positions; (2) Push the particle by the AFM probe tip in contact. This is a 'look-and-move' type of control scheme where the AFM probe cannot image and manipulate the particle at the same time. As Yu et al. [6] showed, the AFM probe and the manipulated nano-object such as the particle or carbon nanotube can only be observed in real-time under a scanning electron microscope (SEM). Thus, in most cases, one of the most significant challenges of nano-manipulation control is the lack of real-time visual feedback during manipulation. Using an SEM for real-time visual feedback is one possible solution, although it limits the application to a vacuum environment which would not be compatible with a wide range of applications involving biological objects (such as DNA, cells, and protein), polymers, or any thing else that requires air or liquid environments. Thus, nano-mechanics model based control using real-time force feedback is one novel approach proposed in [4, 7]. In this approach, contact pushing of a particle should be modeled including the surface forces and contact mechanics (interaction forces during pushing a particle are shown in Figure 5). Here, depending on the physical parameters and the contact pushing control, the particle can slide, roll, spin, stick-slip, or get stuck.

As a second application, an AFM probe can indent soft surfaces with holes as small as 37 nm (480 Gb/in^2 density) for the development of ultrahigh density data storage devices. With the areal densities of conventional magnetic recording technologies eventually reaching well-known physical limits, the ultimate confinement of interaction that the local probe provides renders probe-based recording a natural candidate for extending the storage density

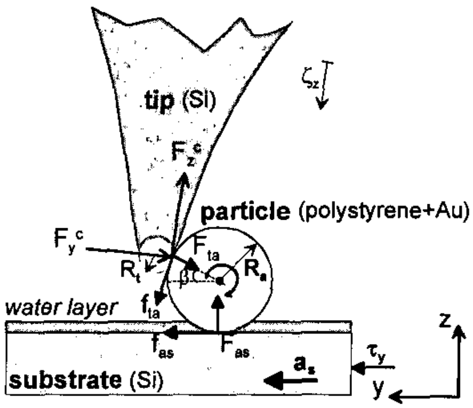

Figure 5 Modeling contact pushing of a nano-particle using an AFM probe: nano-scale surface and contact forces between the tip, particle, and substrate can make the particle slide, roll, spin, stick-slip, or stick.

roadmap. A potentially commercial scanning-probe based data storage system is codenamed "Millipede" at the IBM Zurich. The Millipede [8] exploits parallel operation of very large two-dimensional AFM cantilever arrays currently (an array of 32 x 32 probes currently) with integrated tips and write/read/erase functionality. Data storage speed with a single probe is very limited for commercial data storage rate requirements, resulting in the development of parallel processing with an array of probes. Information is stored as sequences of indentations or no indentations formed by the tips on a nanometer-thick polymer film using thermo-mechanical nano-manipulation. The polymer film is integrated in a micro-scanner with x-y-z motion capabilities and a lateral scanning range on the order of 100 μm. A key challenge is the ability to move and position the polymer substrate under the cantilever array with accuracies of a few nm, which is required for the reliable storage and retrieval of nanometer-size indentations. This is accomplished via a servo loop which uses position information from external sensors to rapidly seek to a target position. For track following, a finer position error is extracted by decoding information stored in the form of special guide marks in dedicated areas of the recording surface. In this work, track following with nm precision is achieved. Current challenges are recording media (polymer) endurance, long term probe tip and media wear, tip uniformity in probe array chip, shock resistance, response to vibration, signal processing, and form factor integration of channel electronics.

The above AFM manipulation examples are mainly 1-D or 2-D; there are almost no 3-D nano-manipulation examples yet. Nain et al. [9] has recently developed a novel 3-D polymer fiber manipulation method by controlled pulling of a liquid polymer using an AFM probe (last nano-manipulation task in Figure 3). After an initial contact with a highly viscous liquid polymer on a flat substrate the adhered polymer is pulled in a controlled 3-D trajectory while it is solidified by thermal heating, UV curing, or solvent evaporation. Solvent evaporation based pulling of PMMA polymer fibers are displayed in Figure 6. This 3-D micro/nano-fiber pulling technology would have wide applications in nano-circuit interconnects and prototyping novel nano-electronic devices, nano-actuators, photonic devices, nano-sensors, and smart materials.

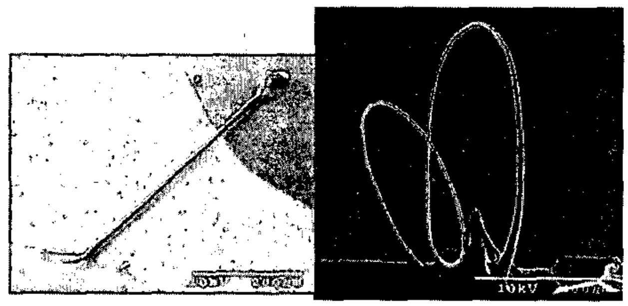

Figure 6 Manufactured three-dimensional PMMA polymer fibers using an AFM probe based pulling and solidification of a liquid polymer on a substrate: a horizontal micro-fiber (left) and 3D pulled fiber (right)

Besides AFM and STM probes, optical tweezers, electrokinetic forces (electrophoresis, dielectrophoresis, traveling waves, etc.), surface acoustic waves, magnetic tweezers, ultrasound, etc. type of tools can be used for nano-manipulation. Optical tweezers are a non-contact nano-manipulator tool, and they apply trapping forces on the order of *piconewton* on the samples in liquid. Therefore, they are widely utilized for bio-nano-manipulation applications where the samples are very fragile. Biological motors, DNA, RNA, viruses, chromatin fibers or any other biomaterials can be manipulated in almost 3-D in their physiological liquid conditions by focusing a laser beam to a point. Castelino et al. [10] introduced a novel method of assembling submicron particles and other building blocks using an array of hundreds of optical traps combined with chemical assembly. The main limitations of optical tweezers based nano-manipulation are: the minimum single object size trapped stably is around 40-50 nm (standard trapped particle size is around 0.5 or 1 μm); precision, distributed, and high-speed x-y-z position control of each trap is challenging; assembled objects should be bonded by chemical and other means to form a mechanically strong and stable material. Finally, electrophoretic and dielectrophoretic forces are used to assemble carbon nanotubes in parallel [11] for nano-electronic circuit applications in the near future. Microfabricated electrodes align and trap the nanotubes in liquid and get short-circuited when any nanotube is contacted to both electrodes. By this method, massively parallel manufacturing of nano-circuits would become possible. Moreover, dielectrophoretic forces have many important biotechnology applications when used to trap, rotate, and sort biological specimens. However, precision control and *in-situ* manufacturing process monitoring is not possible in all of these manipulation processes, which limits the yield and future commercialization.

All of the above nano-manipulation systems have the following main challenges to be solved: 3-D assembly of nano-scale building blocks; real-time and *in-situ* imaging during nano-manipulation; autonomous and intelligent control of the nano-manipulation system; manipulation of entities down to molecular sizes and precision; parallel and distributed control of an array of nano-manipulators.

B. Directed Self-Assembly

Self-assembly offers a new approach to the assembly of multi-component micro- and nano-systems. In directed self-assembly, the components and interactions are tailored by humans to form a desired structure. Electrostatic interactions and surface tension can be used to drive the assembly process on different length scales. As an example, a "Nanoxerographic Printer" is based on electrostatic forces and directed self-assembly to position 5-100 nm sized nano-particles with 100 nm scale resolution from the gas and liquid phase [12]. Such nano-particles can provide a variety of functions and are considered as building blocks of future nanotechnological devices. Examples of devices are single electron transistors, quantum-effect-based lasers, photonic bandgap materials, filters, wave-guides, and high-density data storage. Second he presented his work on surface tension driven self-assembly to assemble microscopic components into electric functional devices and networks with macroscopic dimensions and interfaces. The use of self-assembly to manufacture hybrid integrated circuit assemblies and cylindrical displays was demonstrated. These techniques enable massively parallel and low power consuming nano-assembly systems compared to the robotic nano-assembly approach. However, they lack precision, the minimum assembled object size is currently limited to the nano-object sizes of 40-50 nm, they are random, and non-symmetric structure assembly is challenging.

As another example of directed-self assembly, the growth of micro-pillars as a possible nano-manufacturing technique for micro/nano-fibers inspired by gecko foot-hairs as novel adhesives. Schaffer et al. [13] originally proposed this growth method. In this process, a thin polymer film is deposited on a conductive substrate, and a DC electric field is applied on the film through a micron distance electrode. The surface adhesion and electric field attraction creates the hydrodynamic instability which results in the self-organization of micro/nano-pillars. This method can give regularly spaced micro/nano-structures,

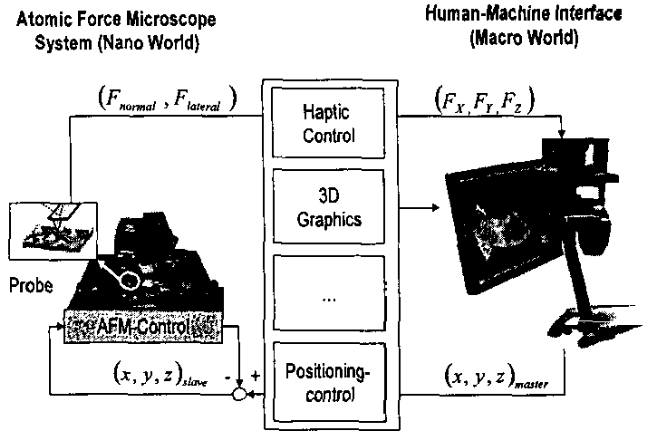

Figure 7 Direct teleoperation control based human-machine interface for an AFM

but the generated aspect ratios are limited and *in-situ* observation and control of the self-organization process is challenging. Currently, it is mainly controlled by an operator by monitoring the polymer surface with an optical microscope. Automatic sensing and control of the micro/nano-structure formation is desirable for mass-production. Therefore, the control of self-assembly process is a novel challenge for the control systems community.

V. HUMAN-MACHINE INTERFACING

Human-machine interfacing of the nano world to human scale is crucial for controlling and interacting with nano-scale systems. Since the knowledge of nano-scale physics and chemistry is still immature, human-machine interfaces using the human intelligence in the control loop would enable robust and flexible operations. Moreover, biological nano-scale systems use complicated and time-varying system applications that always require direct user control. Already, many groups have proposed intuitive user interfaces for SPMs [14-16] and optical tweezers. A human-machine interface for an AFM system is illustrated in Figure 7. This interface displays off-line 3-D AFM image computer graphics and enables real-time scaled nano-force feedback in the operator's finger during a teleoperated nano-scale manipulation and surface interaction. In these user interfaces, the following challenges wait for the controls community's contributions:

- Real-time visual feedback is challenging for AFM user interfaces as in the case of nano-manipulation using AFM probes. Thus, nano-physical models could be used to animate the real-time interaction visually for an intuitive interface.
- Haptic force feedback from the nano world mainly assumes quasi-static interaction, i.e. slow operation. This is because the operator's force sensing bandwidth is very low (around 30 Hz). Thus, it is not possible to

feel the dynamic interactions which are in the KHz-GHz range. Therefore, novel representation methods for the fast dynamic effects as a new modality such as frequency or sound display should be developed.

- Scaling nano-scale forces is a critical issue. They are scaled linearly or nonlinearly [17]. Rigorous methodologies of selecting the optimal scaling factors should be introduced.
- Time-scale differences between macro- and nano-scales necessitate new time-scaled teleoperation control strategies. Since the nano-scale forces are nonlinear and may change in time, stable and robust teleoperation controller design is critical. Even in some cases, nano-scale interactions might not be dissipative, such as a biochemical environment with entities that could have active power and actuation generation capabilities.

VI. MINIATURE MICRO/NANO-ROBOTS

Biomimetics has been a significant inspiration source for novel micro/nano-robots by adapting the smart materials, actuators, sensors, locomotion mechanisms, power sources, and control schemes in nature. Edd *et al.* introduced *E.Coli* bacteria inspired swimming robots that could be used in environmental monitoring of toxic and biochemical materials in aqueous environments and surgical inspection and treatment in the urine system, eyeball cavity, and cerebrospinal fluid. Flagella rotation based propulsion mechanism of *E.Coli* was discussed, and a similar mechanism was proposed with synthetic actuators, tails, rotation mechanism, and materials [19]. Here, the bacteria propulsion mechanism is designed for overcoming the micro-fluidic drag forces at very low Reynold numbers by non-symmetric tail and cilia motion. However, still modeling, construction and control of these miniature swimming robots are open challenges.

Miniature surgical robots monitoring, inspecting and treating diseases inside the human body are one of the promising future directions of nano-robotics field. Miniature and wireless endoscopic micro-capsules were developed in 2001 as an FDA approved commercial product [20] for inspecting the digestive tract diseases. This is the first promising non-invasive miniature device towards a robotic micro-capsule. Teleoperated and semi-autonomous control of these capsules is a new open robotic challenge where currently these capsules have no means of stopping, clamping, and forward or backward locomotion by a direct or indirect sergeant control. By developing novel nano-robotic motion and clamping mechanisms, novel surgical micro/nano-manipulators, drug delivery micro-spray devices, and biochemical nano-sensors, these capsules could evolve to active nano-robotic micro-capsules in the near future.

Moreover, novel biotic and abiotic hybrid and miniature actuator and power sources can be developed by integrating biological organisms with inorganiz micro/nano-structures. A genetically engineered rotating biological motor can be attached to a pivot on a substrate, and a nanofabricated metal propeller is attached to the rotator part of the bio-motor using chemical assembly techniques [21]. When ATP is sent to the liquid buffer, the bio-motor rotates the metal bar with around 8 Hz speed. Thus, chemical energy is used to actuate a hybrid (biological and synthetic) motion system. Secondly, he showed that rat heart stem-cells deposited on compliant microstructures could be used as a hybrid actuator powered by chemical energy. ATP is used to activate the stem-cells which induce mechanical impulse and move the micro-beams with an on/off-control. This is one of the new future directions for nano-robotics in the field of integrating biological systems such as cells and tissues with inorganic micro/nano-structures for novel actuation and powering schemes. These hybrid robots would enable more miniature, adaptive, and robust robotic systems.

Finally, a swarm of miniature nano-robots could be collaborative, multi-functional, robust, and adaptive like an ant colony. Hundreds or thousands of them could be massively manufactured for distributed and collaborative sensing (monitoring and inspection) and manipulation (maintenance, assembly, etc.) applications. Distributed and collaborative control of these multiple nano-robots is a new challenging area for the controls society. Furthermore, emerging behavior and self-learning behavior control of these robots are also open issues.

VII. CONCLUSION

Summarizing the main future open and promising research directions related to micro/nano-scale robotics, systems and control:

- New generation self-tuning and autonomous AFM systems should be developed for optimal, adaptive and fast imaging of nano-scale materials.
- Three-dimensional, parallel and autonomous nano-manipulation systems are required for nano-material characterization, prototyping novel nano-scale devices, sensors and mechanisms, and mass-produced nano-manufacturing applications.
- Control and design of directed self-assembly and self-organization systems are required as an alternative to precision nano-manipulation systems.
- Novel *in-situ* and real-time nano-scale control concepts, back to the ancient times of control, should be developed for dynamic control of high frequency nano-electromechanical systems.
- New hybrid systems integrating and controlling biological entities and micro/nano-electromechanical

systems and using the chemical energy as the power source would be promising for building novel miniature, robust and smart micro/nano-systems.

- Multi-length and multi-time scale nano-mechanics modeling is indispensable, and continuum and molecular dynamics based models should be integrated.
- Novel realistic nano-mechanics simulators using approximate real-time continuum models would enable nano-mechanics training and rapid prototyping of nano-systems.
- Miniature nano-scale robots, sensors, and systems would open novel applications in health care, environmental monitoring, search and rescue, biotechnology, wearable devices, self-organizing displays and robots, and desktop size nano-manufacturing system applications.
- Design and control of a network of miniature nano-systems would open novel distributed, adaptive, robust, and multi-functional sensing and active behavior applications. For this, novel emerging behavior, collaborative, and distributed control schemes should be developed.
- Biomimetics could enable multi-functional, robust and smart novel nano-scale sensors, robots, and materials adapting the nature's solutions to the challenging nano-scale engineering problems.
- *In-situ* monitoring, modeling, metrology, and autonomous control of nano-manufacturing systems are challenging.
- Advanced human-machine interfaces for nano-scale microscopes, robots, and manufacturing systems are indispensable for direct human control on complex and time-varying applications.

Other than above topics, quantum control [22], MEMS control, modeling of biological systems down to molecular scale, and many other newly emerging micro- and nano-scale dynamics, systems and control topics are waiting for the contributions of the systems and controls society.

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