Mobile Microrobot Characterization through Performance-Based Competitions

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ABSTRACT

Recent advances in the design and fabrication of microelectromechanical systems (MEMS) have enabled the development of mobile microrobots that can autonomously navigate and manipulate in controlled environments. It is expected that this technology will be critical in applications as varied as intelligent sensor networks, *in vivo* medical diagnosis and treatment, and adaptive microelectronics. However, many challenges remain, particularly with respect to locomotion, power storage, embedded intelligence, and motion measurement. As a result, the National Institute of Standards and Technology has organized performance-based competitions for mobile microrobots that are designed to: 1) accelerate microrobot development by providing researchers a venue to demonstrate and observe novel technologies, 2) reveal the most pressing technical challenges, and 3) evaluate the most successful methods for locomotion and manipulation at the microscale (e.g., actuation techniques for crawling). This paper will discuss the goals and structure of the competition, results from past competitions, and plans to make performance characterization methods an integral component of future competitions.

Keywords

Microrobotics, microrobots, robot competition, performance characterization

1. INTRODUCTION

Microscale robotics, or microrobotics, has emerged over the last decade as the next wave in intelligent systems. As a result of scaling effects, microrobots have functionalities that will open up application paths that would otherwise have been impossible. Their small size and low unit cost allows them to be embedded into subsystems such as consumer electronics, and their small mass results in extremely high accelerations. Additionally, their size facilitates new modes of operation. As in many systems in nature, microscale robots can form large collaborative networks that can work either together to complete tasks faster or independently to cover more ground. This massive parallelism will result in complex system behaviors that have yet to be explored for macroscale robots. Microrobots are likely to have a major impact on advanced manufacturing, the health care industry, and the continued miniaturization of consumer products over the next two decades. However, this technology faces many new challenges with respect to fabrication, integration, control, power delivery, and embedded intelligence, among many others, which must be addressed for this field to find widespread acceptance.

This paper focuses on a mobile microrobot competition organized by the National Institute of Standards and Technology (NIST) that is designed to accelerate the adoption of this technology by U.S. industries. First, we give an overview of the field with an emphasis on the most successful methods for robot locomotion at the microscale. Next, the goals and structure of the competition are described along with the results from these competitions over the last three years. Difficulties in measuring a number of parameters for microrobots have been identified as a major limiting factor in the development of microrobots. Therefore, a list of measurement needs identified through the framework of the competitions is presented. Finally, plans for future competitions are presented, particularly with respect to the integration of microrobot metrology within the competition so that the performance of different systems can be directly characterized and compared.

2. MOBILE MICROROBOTS

The field of microrobotics is extremely broad and brings together a number of disciplines including microelectromechanical systems (MEMS), precision machine design, biology, materials science, and of course, robotics. Examples of common research thrusts include the manipulation and assembly of MEMS components, insect-inspired flying microrobots, the manipulation of particles and cells in solution, and the mobile microrobots discussed here (see [1] and [2] for an overview.) In all of these cases, either the robot or the manipulated object has microscale dimensions (i.e. between 1 mm and 1 µm). The term *microrobot* has also been used by some to simply mean a small robot (e.g., robots having dimensions on the order of centimeters) but this definition is not utilized here.

The dimensional scaling of robots and manipulated parts down to the microscale presents many challenges in microrobotics, including difficulties in precision fabrication, sensor and actuator integration, power delivery, and the interfacing between the micro- and macroscale domains. Most importantly, though, is the

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way in which the role of various forces changes between the macro- and microscales. Due to scaling effects [3], electrostatic, van der Waals, and capillary forces – among others – are significantly larger than inertial forces at the microscale. As a result, adhesion between robots, parts, and the surfaces that they interact with can limit dexterity and mobility. This is particularly true for mobile microrobots, which can easily become stuck while moving on a surface. Therefore, methods of locomotion that can overcome these adhesive forces, or even exploit them, are needed.

One of the first and most common methods of locomotion is based on the electrostatic scratch drive actuator. The untethered scratch drive actuator, developed by Donald et al. [4], consists of a conductive plate that has a bushing positioned on the bottom side of the plate near one side. When placed on a surface the scratch drive actuator sits at a slight angle to the surface due to the placement of this bushing. Motion in the plane is generated by applying an electrostatic force between the plate and surface that is large enough to make the plate snap down to the surface. Consequently, the edge of the plate that contains the bushing moves forward by a small increment (10 nm to 50 nm). When the electrostatic force is removed, the plate straightens but remains in the newly obtained planar position. The repetition of this sequence has been shown to yield repeatable motion with velocities approaching 2 mm/s. The electrostatic force is generated using an engineered surface composed of an interdigitated electrode array and a dielectric coating. By applying a voltage across the electrodes, the electrostatic force can be cycled at high rates (100 kHz) to yield high speed motion. However, this approach only provides unidirectional straight-line motion. Therefore, a turning arm has been added to the scratch drive actuator so that the microrobot can turn, leading to global controllability of the robot in the plane [5].

Electromagnetic forces have also been shown to be effective in actuating microrobots. Floyd, Pawashe, and Sitti [6] have demonstrated microrobots fabricated from a hard magnetic material, which can be as simple as a solid magnet block. Forces are exerted on the microrobot by uniform magnetic fields generated by macroscale multi-axis electromagnetic coils. By adjusting the control currents applied to the coils, the microrobot can be moved on a planar surface. The most repeatable motion has been achieved by applying a pulsed current signal along the desired motion direction, which results in a stick-slip motion caused by balancing the friction forces and electromagnetic forces.

Another electromagnetic actuation approach developed by Vollmers et al. [7] utilizes a resonant drive mechanism. Similar to [6], a set of electromagnetic coils is used to generate a controllable uniform magnetic field in the workspace of the microrobot. However, the microrobot's mechanical design is significantly different. The microrobot consists of two nickel blocks of different size that are connected by a metal spring. The magnetic field is modulated at the first resonant frequency of the mass-spring system to cause the two ferromagnetic blocks to vibrate relative to one another. When the vibration amplitude is large enough to cause the blocks to collide, the resulting impact force moves the microrobot in the plane. In addition to the electromagnetic forces, an electrostatic force is applied normal to the surface by operating the robot on an interdigitated electrode array as described above for scratch drive actuators. The electrostatic force is used to clamp the microrobot to the surface when the two masses are separated. Just before the two masses collide, the clamp is removed and the microrobot moves forward after the collision in a controllable increment.

Although other methods of locomotion have been demonstrated, including thermal impact drives [8] and piezoelectric crawlers [9], electrostatic and electromagnetic locomotion have been the dominant methods for microrobots. Each of the methods discussed above has also been extended to multi-robot control, which is essential in realizing the parallelism that makes microrobotic systems so powerful. Donald, Levey, and Paprotny [10] have shown that multiple electrostatic microrobots can operate on a single electrode array by designing each robot to have independent snap-in voltages for their scratch drive and turning arm. The electromagnetic robot in [6] has been shown to be extendable to parallel operation using a grid of independent electrode arrays for electrostatic clamping [11]. Finally, Kratochvil et al. [12] have demonstrated multi-robot operation using the resonant drive mechanism described in [7] by designing robots to have unique resonant frequencies, which can all be addressed through a single control signal for each degree of freedom of motion. Continued development of multi-microrobot systems is needed to fully utilize the nascent capabilities of microrobots working together collaboratively.

3. PAST COMPETITIONS

The mobile microrobot technologies discussed in the previous section have all been developed over the past decade and with the greatest momentum in the past three years. Although this field is in its infancy, it is a clear extension of the MEMS and robotics technologies that have become integral to many consumer products, manufacturing capabilities, biomedical tools, and military systems. However, mobile microrobotics is also a disruptive technology because microrobot designs are often not compatible with existing MEMS fabrication methods and the complexity of microrobot control presents new challenges in communications and power transmission at the microscale. Therefore, this field will require considerable investment to transition the technology to the marketplace. As a result, NIST has organized competitions over the past three years that are designed to accelerate development in this field while mitigating the risks in adoption of this technology by U.S. industries. The main goals of the competitions are to:

Assess the State of the Art - The competitions bring together a number of experts in the field along with their latest developments in mobile microrobotics. This provides the best vantage point to assess what is currently feasible and where this technology is going.

Accelerate Development - Competing teams must focus their technologies toward specific microrobot tasks in the competition and must meet hard deadlines to participate. This pressure provides considerable motivation to accelerate their research.

Provide Head-to-Head Comparisons - The competitions provide a unique opportunity to compare disparate approaches for realizing controllable microrobots that would not be possible by studying the technical literature alone. This has been particularly useful in evaluating the controllability and repeatability for different methods of locomotion.

Identify Measurement Needs - There are many measurements routinely performed on macroscale robots that cannot be performed on mobile microrobots because of their small size and high speed. NIST gains considerable insight into the shortcomings of existing measurement methods, which motivates the development of new measurement techniques that will aid in the adoption of this technology by U.S. industries.

NIST has organized the annual series of microrobotic performance competitions, beginning in 2007, in association with the RoboCup Federation. The competition events, while presented to fit the soccer theme of the RoboCup organization, are structured to test microrobotic systems in the key performance areas of mobility, maneuverability, and manipulation capability. Robots in these competitions are required to be no bigger than 300 micrometers in their largest dimension, and to have no wires or physical tethers extending outside of a 300 micrometer cube. Participating teams had to complete the following three tasks on a field of play based on a soccer pitch that measures 2 mm long and 2 mm wide and has a goal at each end:

The Two-Millimeter Dash
The microrobot must traverse a straight-line distance of two millimeters in as little time as possible, beginning from, and ending at, a complete stop within a defined area. Most obviously, this event measures the speed of a microrobot, but in practice the responsiveness of the robot to start and stop signals is often the critical capability.

The Slalom Drill
The microrobot must navigate the same two-millimeter course as before, this time avoiding a set of obstacles placed in its path. The number of obstacles is increased as necessary to force more complex paths and to differentiate higher levels of maneuverability.

The Shootout
The microrobot must maneuver through an obstacle course, collecting and delivering microscale silicon discs (soccer balls) to a goal location (see Fig. 1). This performance metric tests the ability of the robot to perform planar pushing manipulation tasks.

Participating teams have the option to attempt these tasks autonomously, using image feedback from a microscope and digital camera, or by teleoperation. However, since teleoperation is easier to implement, a penalty is assessed for this mode of operation. Figure 2 shows several of the microrobots that have been entered in the competition, each of which to date has been based exclusively on the electrostatic and electromagnetic locomotion methods described in the previous section.

So far, only one team has been able to complete The Two-Millimeter Dash and The Slalom Drill autonomously (ETH Zürich), while two teams have completed them by teleoperation. No team has completed The Shootout using the soccer ball shown in Fig. 1, but ETH Zürich has demonstrated goal-scoring with soccer balls developed specifically for their robot. These shortcomings point to the high level of difficulty of the tasks in this competition.

Over the three years that the NIST microrobotics competition program has been operating, a broad variety of microrobotic systems has been evaluated. Tested robots include those operating based on electrostatic attraction, soft magnetic resonant actuators,

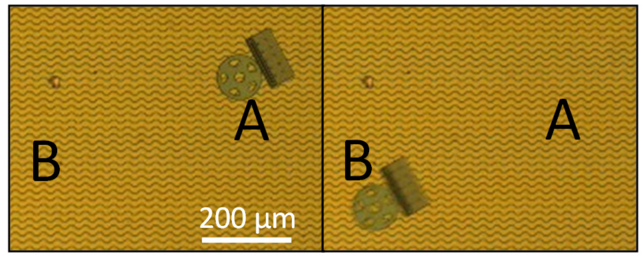

Figure 1 A sequence of two images showing an electrostatic microrobot moving a silicon disc (soccer ball) from point A to point B (elapsed time ≈ 3.5 s)

and hard magnetic actuators. Masses of the competing robots have ranged from 10s of nanograms up to 10 micrograms.Material combinations used for the microrobots have included silicon and chromium; metal thin films and thermoset polymers; nickel and gold; and rare-earth magnetic materials. The microfabrication protocols used to manufacture the evaluated microrobots have included surface micromachining processes, high-aspect-ratio electroplating, and laser micromachining. Despite this tremendous diversity of microrobotic technologies, ***all*** of the evaluated systems have converged on the same class of gaits.

In contrast to the legged or wheeled modes of locomotion typical of macro-scale robotic systems, which seek to minimize friction, the class of gaits that has become most prevalent in microrobotics consists of a slip-stick motion in which frictional anisotropies are exploited. Typically, the microrobot slides against friction in one part of the motion cycle, then is held fast by friction forces during the recovery portion of the motion cycle.

The success of the slip-stick class of gaits leads to many more questions than answers about the future of microrobotic technologies. Friction at such small size scales typically exhibits non-Amontonian behavior, in which the friction force is not linearly proportional to the normal force. Non-Amontonian friction regimes remain poorly understood and can be difficult to model or predict. In addition, the normal contact forces can change by orders of magnitude in response to variations in the environment or operating surface and in response to wear and electrostatic charging of the contacting surfaces.

Reliability is a significant challenge for microrobotic systems, with performance variations from robot to robot of the same design and for individual robots over time. Operable lifetimes range from minutes to hours, and failure modes are poorly understood.

The operating mechanisms for microrobotic devices are understood primarily in abstract terms, so that optimization of microrobot performance is accomplished mostly on a trial and error basis. For example, robot motions corresponding to new resonant modes were discovered in the midst of the 2009 competition by changing the electrical input parameters.

More detailed models of microrobot operation are required, along with the experimental means to validate them. Validating models of operation is made difficult by the fact that discrete microrobot motions are often much smaller than the microrobots themselves and can be difficult to observe. For example, single steps of the scratch drive actuator are thought to be as small as 10 nm.

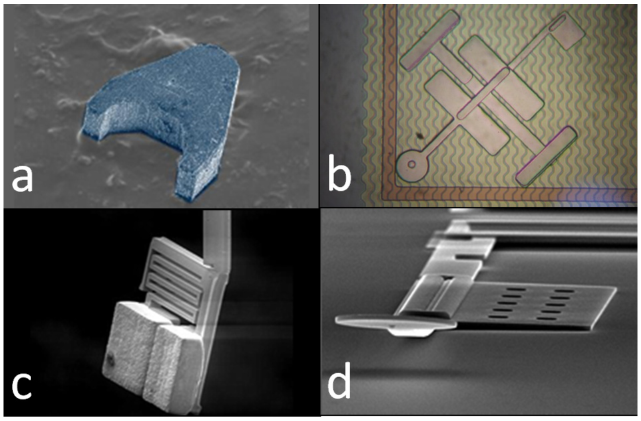

Figure 2 Various microrobots that have been demonstrated in previous competitions: a) hard magnet microrobot (Carnegie Mellon University), b) polymer-based electrostatic microrobot (Simon Fraser University), c) resonant electromagnetic microrobot (ETH Zürich), and d) electrostatic microrobot (U.S. Naval Academy).

4. MEASUREMENT NEEDS

The locomotion mechanics for most microrobots are not understood in detail due to complex force interactions at the micro- and nanoscales. As a result, precision measurement of the physical behavior of microrobots will play a significant role in modeling locomotion mechanics, developing new microrobot designs, and pushing their performance limits. The list below highlights the most pressing measurement needs, which has considerable overlap with those needed for current and prospective commercial MEMS devices. In many cases, suitable instrumentation and methods for these measurements are currently not available.

- *Coarse Motion*. Characterizing the motion of the device on the field of operation. The most successful mobile microrobots utilize a slip-stick gait. Tools are needed to understand the dynamics of this motion as well as the interaction between the microrobot and the surface as the microrobot makes nominally identical steps in a constant direction, as well as how the robot behaves as its direction of motion changes.
- *Fine Motion*. Characterizing the motion of subsystems of the microrobots at the nanoscale; in particular, the motion of the actuators that determine the direction and rate of movement.
- *Actuation Force and Stiffness*. Characterizing the output force of actuators and the stiffness of microrobot components will further understanding of modes of locomotion. Instrumentation that can measure multi-axis forces on the order of micronewtons with measurement bandwidth greater than 100 kHz must be developed.
- *Electromagnetic Properties*. Although the applied magnetic and/or electrostatic fields can be estimated for free space conditions, the presence of the microrobot and the region of operation means that the actual magnetic and/or electrostatic fields applied to the microrobot may differ substantially from the free space estimate. Therefore, tools are needed for local measurement of the magnetic flux density and capacitance.
- *Materials Properties*. Materials at the microscale are dominated by surface, rather than bulk, properties. Novel measurement methods to determine surface properties of microscale elements are needed to characterize the elements that compose a microrobot.
- *Friction and Adhesion*. At the microscale, friction and adhesion forces dwarf inertial forces due to the high surface area-to-mass ratio of microrobots. Methods for measuring non-Amontonian friction, adhesion forces (van der Waals forces, capillary forces, etc.), and quantum mechanical effects are needed.
- *Reliability*. The original promise of MEMS devices in the 1980s was that of small-scale machines incorporating gears and complex motion. This promise has yet to be realized primarily due to the poor reliability of MEMS devices with contact motions. Microrobots provide a platform for evaluating the reliability of a range of microscale contact modes and observing how their performance evolves over time.
- *Environmental Sensitivity*. For microrobots to meet many of the challenges elucidated previously, they must be able to function in a wide variety of environments (temperature, humidity, air, water, etc.). Performance metrics for microrobots to operate under varied environmental conditions will assist in overcoming existing requirements for tightly controlled operational environments.

5. PLANS FOR FUTURE COMPETITIONS

Although significant qualitative data has been captured in previous competitions, quantitative measurements have not been made while the microrobots performed competition tasks. As discussed in the previous section, new measurement methods and extensive data sets are critical for improved understanding of microrobot operation. The competition presents an excellent opportunity to measure the performance of a number of different technologies that would generally not be available in a single research laboratory. Therefore, we intend to incorporate microrobot metrology into the competition, which will be used to evaluate technologies and provide new insights into the mechanics of microrobots.

Unfortunately, many of the measurement technologies required to meet the needs listed in the previous section are complex, expensive, and not portable. However, as a first step in building performance characterization methods into the competition, a high-speed digital video system will be integrated into the competition microscope and an automated image processing application will be developed to provide coarse motion measurements with high motion bandwidth (> 500 Hz). The software will be capable of providing the planar coordinates (x, y, θ) of multiple microrobots and other objects (obstacles, manipulated parts) as a function of time, as well as other variables that can be extrapolated from this data. These include microrobot velocity, acceleration, trajectory tracking precision, turn radius, and motion repeatability, as well as an analysis of their kinematic constraints. Although it is expected that the image processing will be performed off-line for high-speed video, this tool will also be used for visual feedback when operating at slower frame rates (< 60 fps).

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