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NIST and IEEE Challenge for MagPieR

The Fastest Mobile Microrobots in the World

Recent advances in micro/nanotechnologies and microelectromechanical systems have enabled micromachined mobile agents. Highly dynamic mobile microrobots are believed to open the gate for various future applications. However, at the submillimeter scale, the adhesion effects dominate physics, especially in the air environment. Although many studies have been performed to avoid or reduce this effect, the sticking phenomena are still one of the biggest challenges in achieving highly dynamic micromobile robots. Subsequently, intrinsic challenges at the given scale (hundreds of micrometers) are the powering technique themselves. Although often designed from active materials, actuation may only be performed by means of various external fields that often require a lot of space around the scene. In this context, the National Insti-tute of Standards and Technology (NIST) and the IEEE initiated an annual state-of-the-art microrobotics chal-lenge, boosting the development of novel mobile agents with precise and highly dynamic propulsion mechanisms and controllability. During our first participation in this competition in 2010, the French team Centre National de la Recherche Scientifique (CNRS) proposed a magnetic and piezoelectric mobile microrobot called MagPieR, which dramatically enhanced the propulsion speed to 28 ms for the so-called 2-mm dash task. It literally cut the former
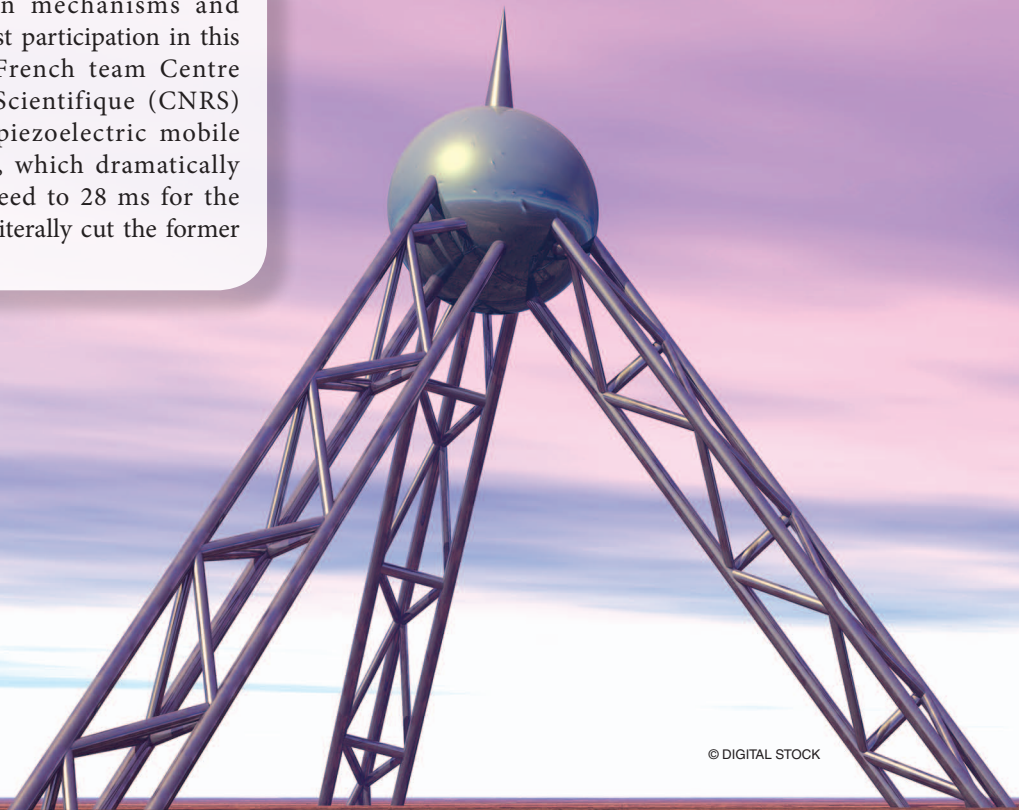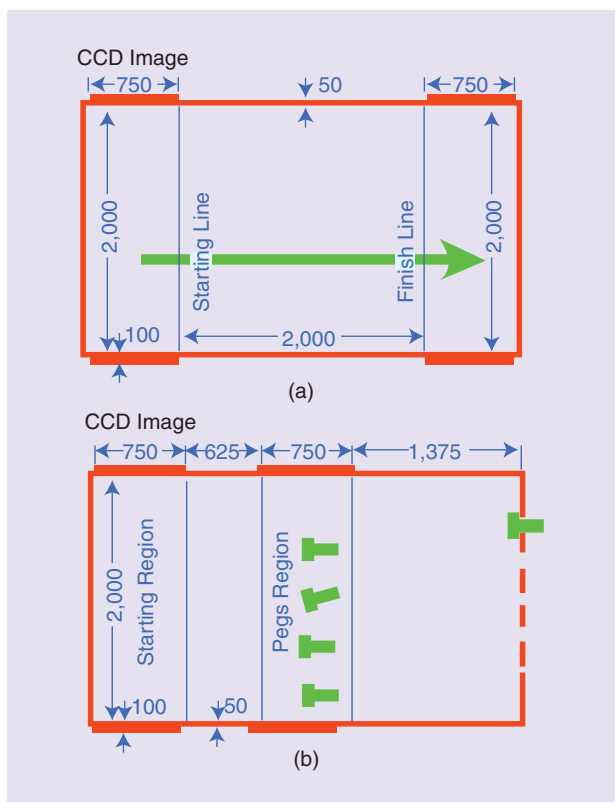
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Figure 1. (a) The 2-mm dash and (b) the microassembly task arenas as in the 2010 MMC edition [4]. The dimensions are in micrometers.

record to a quarter. In the meantime, during the 2011 challenge, MagPieR won the mobility challenge thanks to some optimized coil setup and control law. The continuous technical advances in terms of dynamic performance are now shifting, and the focus of the next challenge is more agile-demanding and controllable tasks. Combining different physical effects is a promising key for the future of highly dynamic mobile microsystems and associated applications in micromanipulation, microassembly, or minimally invasive surgery.

NIST and IEEE Mobile Microrobotics Challenge

Inspired in 2007 by the well-known RoboCup [1] International Robotics Soccer Competition that was already in its tenth year with hundreds of participating teams, a group of researchers from NIST initiated the Nanogram League within the RoboCup. Tiny microrobots of $300 \times 300 \ \mu$m size placed into 2.5-mm playgrounds were invited to perform soccer-related tasks, such as a 2-mm dash, slalom drill, and microball handling. Given the radical dimensional constraints, the Nanogram Challenge was unique with respect to other ongoing microrobot contests, such as the Micro Robot Maze Contest [2], where the maximum dimensions are in centimeters, and the challenge is set for optimum integration of discrete elements (power supply, electronics, and actuators). Under the

millimeter, at the true microscale, all standard robotics components are inadequate, and the actuating principles are restricted to external ones, such as magnetic, electromagnetic (laser), and electrostatic (scratch-drive mechanisms). Thus, the challenge is to put on state-of-the-art micromachining and advanced wireless control under adverse attractive or repulsive effects (capillary, adhesion, and electrostatic).

In 2010, the Nanogram Robocup Competition was renamed the NIST IEEE Mobile Microrobotics Challenge (MMC) and was held in Anchorage, Alaska, during the IEEE International Conference of Robotics and Automation (ICRA) [3]. With the support from the IEEE, the MMC gained a reputation with 12 enrolled teams, of which seven were finally able to submit the qualification video imposed for participation.

To accommodate a larger panel of untethered propulsion principles, the maximum size of the microrobots was extended to a sphere of 600 μm in diameter. The arenas were furnished by the competing teams and strictly imposed to 2 $\times$ 3.5 mm with solid borders, as shown in Figure 1.

MMC 2010 consisted of three events organized along three successive days, 4–6 May 2010, as follows:
- The classic 2-mm dash, where the agents positioned behind a virtual starting line had to cross the finish line at 2-mm distance as fast as possible and then perform a complete stop. The counting was triggered by the first moving frame [150 frames per second (fps) camera], and the final score was the quadratic mean [root mean square (RMS)] of three tries calculated from the first moving frame to the last frame in a complete stop position.
- The microassembly event, in which the microrobot had to insert a series of small T-shaped pieces into appropriate holes. The width–length proportions of these small pegs were imposed, but their absolute dimensions were to be chosen by the competing teams (according to the size of the microrobots) with up to 600 μm being the largest dimension. Microassembly event trial score was the number of pegs fully inserted, whose caps touched both sides of the boundary of the hole, as shown in Figure 1(b).
- The freestyle event, in which the competing teams had to demonstrate a panel of chosen complex task performances within a maximum period of 5 min. The competition was evaluated by a board of external judges, scoring the tasks on a scale from one to ten.

The competing teams in the 2010 NIST Challenge were from Europe and North America. From the seven qualified teams, six teams finally participated, showing successful actuation based on (electro)magnetic principles. These untethered methods are considered a privileged approach because, at this scale, microrobots can neither actually embark energy sources nor process units similar to their centimeter-size counterparts. The participating

teams and their respective applications are summarized in alphabetic order as follows:

- Carnegie Mellon University (CMU) has been a veteran participant since the Nanogram RoboCup. Their 2010 agent (Mag-μBot) was a polyurethane body filled with NdFeB particles. The resulting permanent magnet was placed into a classical three-dimensional (3-D) Helmoltz coil setup, operating a stick-slip movement on the surface [5], which is operated by pulsed magnetic fields. Subsequently, the CMU team added a switchable electrostatic clamping grid on the surface to demonstrate the control of multiple collaborative agents (i.e., docking and undocking) [6].

- CNRS is our French team, consisting of graduate researchers from the FEMTO-ST institute located in Besançon and the Institut des Systèmes Intelligents et de Robotique (ISIR) in Paris. Our model, called MagPieR was developed in early 2010 and competed for the first time in Alaska. See the "MagPier Microrobot—Designed for Fast Actuation" section for more details.

- Eidgen össische Technische Hochschule Zürich (ETHZ) is the well-known Swiss Federal Institute of Technology Zurich, comprising the Institute of Robotics and Intelligent Systems (IRIS). They are the successful designers of the ingenious MagMites microrobot actuated by a resonant impact-driven method using two nickel inertial masses connected by a gold spring and powered by an oscillating magnetic field [7]. In 2010, the ETHZ team replaced MagMites with MiniMag, an NdFeB agent capable of five degrees of freedom (5 DoF) by means of magnetic coupled fields issued from eight electromagnets. The 3-D feedback control was ensured by visual servoing. The explored environment was aqueous, providing an average speed but unmatched position accuracy. MiniMag is a small-scale development of Octo-Mag [8], an instrument used for medical applications.

- Stevens Institute of Technology from New Jersey presented μMAB, the microscale magnetostrictive asymmetric thin film bimorph microrobot [9], consisting of layers of nickel and copper. Friction coefficient was modulated by out-of-plane flexural vibration induced by oscillating fields. Subsequently, an in-plane gradient field component allowed steering and propulsion. This principle seems similar to that of MagPieR, except that we independently chose piezoelectric out-of-plane actuation.

- The U.S. Naval Academy (USNA) is one of the oldest participants in the MMC [10], having been involved since 2007. Their Tesla model was made from a base layer of nickel with three polysilicon arms. The operating principle relies on magnetic field gradients in a viscous environment.

- The University of Waterloo (UW) from Canada is a team of all undergraduate students. Their electromagnetic microrobot actuation (EMMA) agent consisted of an electroplated layer of magnetic alloy (Co-Ni-Mn-P)

on silicon patterned with SU-8 photoresist (similar to most of the teams). The actuation method consisted of a combination of permanent and induction coils actuated by linear stages under the arena surface.

Entries and Scores

With regard to participation, we noted a net increase in the interest in that year's challenge with 12 initially registered teams. The six finalists of the MMC 2010 Challenge proposed magnetic principles, each solution showing at least one original concept. Magnetic methods remained a privi-leged source with long-term potential (e.g., bacterial-like nanopropellers, helices), although other propulsion princi-ples, such as thermal laser [11], dielectrophoresis [12], and bipolar electrochemistry [13] will probably be presented next year.

Our MagPieR model was particularly designed for fast actuation, and as a result, it not only achieved first place in the 2-mm dash with an RMS score of 32 ms (28 ms being the best try) but also cut the former record held by ETHZ, concluding the day's surprise (Figure 2). The following were the scores: CMU: 78 ms; UW: 852 ms, and ETHZ: 1.109 s. With regard to the microassembly task, ETHZ was the clear winner, raising applause for their outstanding five-dimensional (5-D) capabilities. The last day was dedicated to the freestyle competition, in which ETHZ won again, showing sophisticated trajectory capabilities. They were closely followed by CMU, which demonstrated collaborative capabilities.

> The new MagPieR microrobot was particularly designed for breaking the speed record, providing a planar magnetic actuation with an optimized coils setup, and a subsequent piezoelectric actuation for improved sliding condition.

The 2010 MMC event was one of the largest events that attracted much interest among the IEEE ICRA robotic challenges, pointing out that frontier research may be advanced through competitions, where the teams work hard, but also have lots of fun. MMC 2010 was publicized online in *IEEE Spectrum*[14] and in other magazines.

MagPier Microrobot—Designed for Fast Actuation

The new MagPieR microrobot was particularly designed for breaking the speed record, providing a planar magnetic actuation with an optimized coil setup and a subseq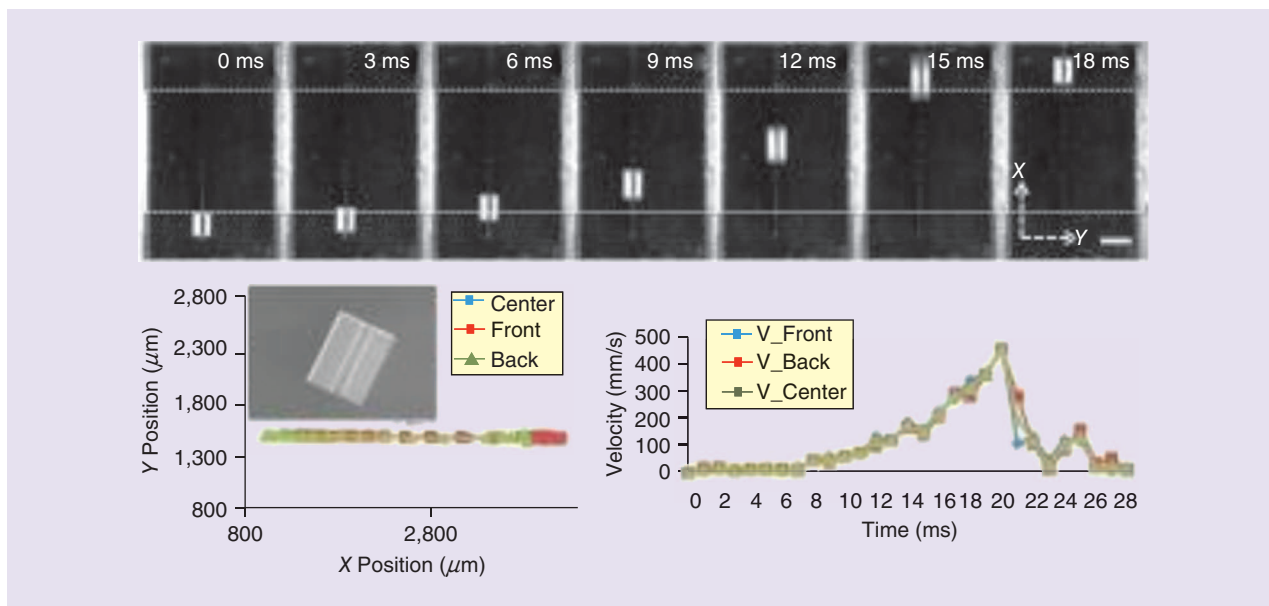uent piezoelectric actuation for improved sliding condition. The agent is composed of two heterostructure layers: a top ferromagnetic material layer (electroplated nickel) for magnetic gradient propulsion and a bulk piezoelectric material [lead

Figure 2. The captured motions during 2-mm dash task and their tracked trajectory plots of MagPieR. The current imposed value was 1.2 A (the scale bar is 500 μm).

magnesium niobate-lead titanate (PMN-PT)] for out-of-plane vibration. The microrobot is intended to overcome surface friction. It can move on the horizontal plane of a planar capacitor whose bottom electrode is the arena substrate itself while the top electrode is an optically transparent conductive glass (tin-doped indium oxide, ITO).

Piezo PMN-PT material is by far superior to the classical lead zirconate titanate (PZT) ceramics due to the very high longitudinal d_{33} piezoelectric coefficient (3,100 pC/N when compared with 590 pC/N). The major strain capability of the new PMN-PT materials made this type of actuation possible (which we did not observe for PZTs).
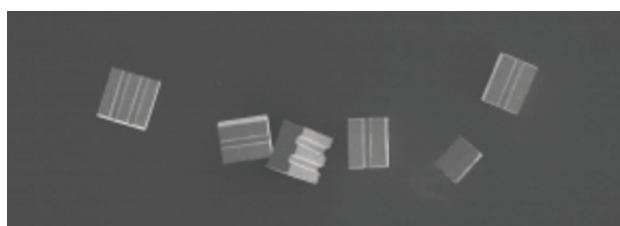
> We chose the MagPieR with the thread crossing the longitudinal axis on the ferromagnetic nickel layer to show the better-guided linear propulsion.

Figure 3. Scanning electron microscope (SEM) images of several MagPieR agents: Type I images are the square ones featuring two trenches while Type II images are the rectangular ones with a single microtrench. (Photo courtesy of FEMTO-ST Institute.)

The microrobot fabrication process consisted of cutting the PMN-PT substrate into centimeter-size plates, sputtering a Cu-Cr primer layer at the top side, sputtering a Ti-Cr layer at the bottom side, protecting the resin at the bottom side, Ni electroplating on the top side, saw dicing into small square or rectangular samples, and saw trenching of the top Ni layer.

The final structures were 224-μm high, of which 200 μm was the PMN-PT layer and 24 μm was the Ni layer, as shown in Figures 3 and 4(a). We used two different geometries, square and rectangular:

- Type I, $388 \times 388 \times 224$ μm^3 with two 50-μm-wide threads
- Type II, $388 \times 300 \times 224$ μm^3 with one 50-μm-wide thread.

The densities of PMN-PT and Ni were almost identical, but the former material was more mechanically compliant and fragile. The mass of the Type II model, which competed in the challenge, was 0.21 mg, of which less than 9% consisted of the ferromagnetic core.

Saw trenching was intended to allow for a faster and more oscillatory-free orientation along the magnetic field lines. Similarly, we tested bulk samples (without trenches) that naturally showed faster speeds due to the increased amount of Ni, but they performed, as expected, in a more unstable manner.

The microrobot was positioned into a self-fabricated 3.5×2.0 mm^2 arena, whose dimensions were imposed by the competition organizers [Figure 1(a)]. To visualize the scene perpendicularly, the ITO-conductive glass was considered for the top electrode. The microrobot and the arena were packaged into a 6.5×6.5 mm^2 assembly sealed with two diagonal flanges, as shown in Figure 5, and was

made of four distinctive layers. This avoided contamination of dust particles and also allowed quick arena interchange. We noticed that our setup was mostly miniaturized and provided with embedded electronics.

Some opposite corners in the arena layers were cut in a manner that allowed electrical access to the electrodes [Figure 5(b)]. The layers are as follows:

- A top conductive ITO glass acting as a transparent top electrode (high voltage) is bonded to a conductive wire.
- An intermediate glass layer of 155 μm plays the role of a dielectric isolation that was cut annularly by an ultrasound machine.
- An intermediate silicon layer of 110 μm that was microfabricated at both the sides using a clean room process: Gold and aluminum sputtering, photolithography, and deep reactive ion etching (DRIE) techniques. This layer insured the border walls and the marks of the virtual starting and finish lines.
- A bottom silicon piece cut from a wafer whose surface was metalized by Cr-Al sputtering. This layer played as the ground electrode.

The internal height of the arena was 255 μm, fairly superior to the one of the agent (224 μm). The microrobot traction was performed using a mix of one high-voltage signal and four high-current signals. A series of high-voltage square pulses (300 V, 400 Hz) provided out-of-plane piezoelectric strain, while the nickel mass acted inertial, making the robot to perform micrometer-range jumps by losing the adhesion contact with the arena surface. Simultaneously, the external magnetic field gradients (between 3 and 30 mT/mm) issued by four orthogonal coils with iron core insured the attractive translation force and steering. Quick breaking could be performed by stopping the electrostatic field impulses and by reversing the magnetic field gradient.

There are two possible operating strategies:

- *Continuous driving*, where the magnetic force is higher, equal, or slightly lower than the friction threshold (maximum friction value). The threshold usually corresponds to a gradient from 0.2 to 5 mT/mm depending on the surface state and humidity. Upon time constant signals, the resulting actuation is monotonically accelerated. Piezoelectric effect serves to improve the sliding conditions. For instance, if we apply a magnetic gradient just slightly under the friction threshold, the microrobot will not start moving until the electric field impulses trigger displacement. In the case of

magnetic gradients above the friction threshold, the microrobot can move slowly (without electric field), but addition of the electric field pulses significantly improves speed as the microrobot loses contact with the base surface [see Figure 4(b)]. This operating mode provides very high speeds (see the "Actuation Results" section), and was used during the challenge for the 2-mm dash. The French team won the event with an RMS score of 32 ms and a record of 28 ms.

- *Short impulse driving*, when the magnetic force is kept well below the friction threshold. In this case, small amounts of actuation (leaps) are provided for each piezoelectric
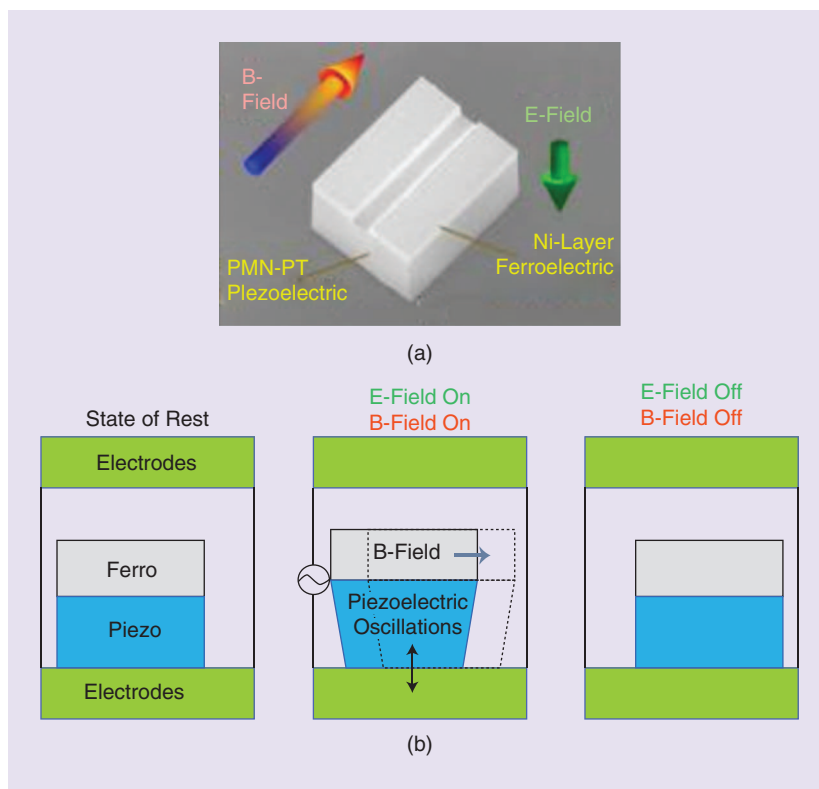

Figure 4. (a) An SEM image of a Type II agent combined with a schematic of magnetic and electrostatic field directions. The microrobot is 388 × 300 × 224 μm³. (b) The mechanism of locomotion: electric field is generated between both the electrodes of top and bottom surfaces to generate strain in the PMN-PT layer, vertical oscillations can reduce the adhesion force between the surface and microrobots, the microrobots can move along the magnetic field gradient, and, finally, the electric field is cut when the microrobot is reached to the target position (drawing not to scale).

impulse. This is a step-by-step actuation, similar to the stick-slip conditions. Current works are in progress to achieve useful results for the next NIST challenges.

Actuation Results

After the contest, we characterized the propulsion performance of MagPieR. The strategy to achieve the fastest motion has also been described, and the performance has been compared with other state-of-the-art propulsion mechanisms.

The 2-mm dash task at the NIST and IEEE MMC 2010 consisted of measuring the travel time from start to complete stop. The measurement was carried out using a high-speed camera analysis during the MagPieR motion from start to goal line. MagPieR has several strategies to achieve propulsion efficiency by overcoming surface friction during their propulsions. First, the piezoelectric oscillation in the vertical axis can reduce surface friction. Second, the linearity during its propulsion is assured by passively guided motion in parallel to magnetic field gradient. Third, the MagPieR is stopped at the closest point to the goal line.

We chose the MagPieR with the thread crossing the longitudinal axis on the ferromagnetic nickel layer to show the better-guided linear propulsion. We aimed to reveal the effect of this thread correlated to the propulsion linearity. For
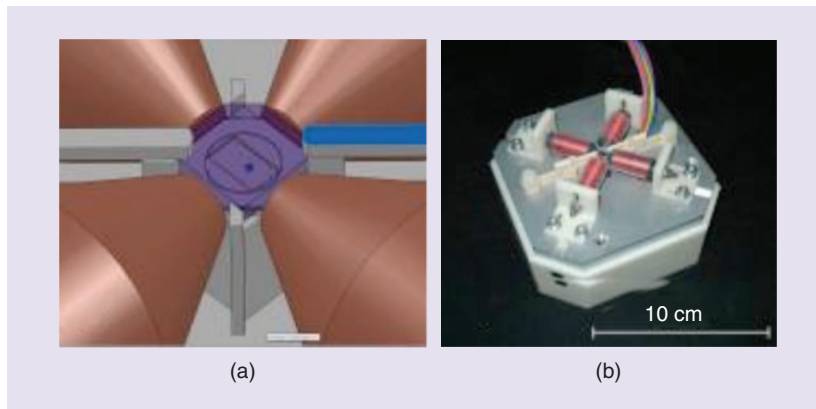
> The National Institute of Standards and Technology (NIST) and IEEE initiated an Annual State-of-the-Art Microrobotics Challenge, boosting the development of novel mobile agents with precise and highly dynamic propulsion mechanisms and controllability.
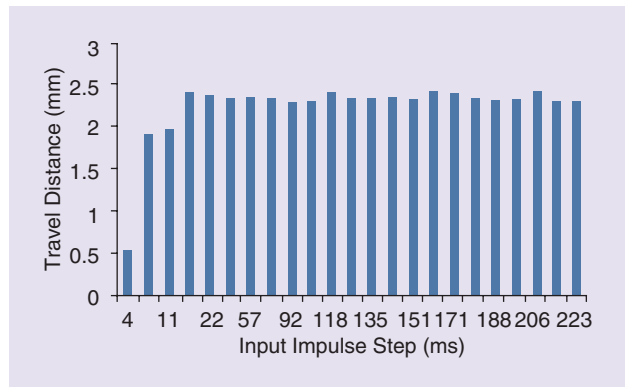
Figure 6. Propulsion characteristics of stopping distances depending on the input pulse steps to MagPieR.

a better precise comparison in propulsion linearity, a high-speed camera with 1,000 frames/s was used to record the videos during the 2-mm dash task.

Figure 2 shows a series of images at 3-ms interval, captured from the original movie taken at 1,000 frames/s. The propulsion of MagPieR was revealed to have linearity even after it passed the goal line. It should be noted here that the motion of MagPieR was shown in four different distinctive steps. First, it aligns through the electromagnetic field gradient, continues the linear propulsion, then passes the goal line, collides to the wall behind the goal line, and finally stops. This implies that we can further improve the propulsion performance by modifying the input pulse time and controlling the propulsion linearity from design parameters.

As shown in the velocity plots of MagPieR propulsion, it collided at around 23 ms (the velocity is zero), which shows that redundant travel occurs after collision to the wall. Considering that the travel time estimation for a 2-mm dash task measures the time between the start line and a complete stop behind the goal line, this redundant motion can be avoided to further improve the record by about 25–30%.

To avoid the collision to the wall and make the MagPieR stop at the closest distance from the goal line, we aimed to find the optimal input step pulse. For this purpose, we characterized the travel distances of MagPieR with different input impulse times. The measured result is presented in Figure 6. As a result, 14 ms of input impulse time stops MagPieR the closest to the goal line. This parameter could reduce the travel time by avoiding the redundant travel behind the goal line from collision and bouncing. Further, surface optimization can even enhance the current propulsion performance.

Furthermore, the initial alignment is important to achieve the propulsion linearity. When the thread is initially well aligned through the field, additional motion required for the alignment (a damped oscillatory rotation) that adds

Figure 5. (a) The setup CAD schematic showing the coils and the interchangeable arena. The arena consists of four layers (from top to bottom): An ITO glass top electrode (1.1 mm), a glass spacer (155 μm), a silicon arena border (110 μm), and, finally, a silicon base substrate acting as the ground electrode (400 μm). (b) The photo of the setup.

Table 1. Propulsion performance comparison of mobile microrobots.

	MiniMag	EMMA	Mag-μBot	MagPieR
Length (μm)	~300	~500	~500	~400
Velocity (mm/s)	1.8	2.3	25.6	71.4
Body lengths/s	6$\times$	4.6$\times$	51.2$\times$	178.5$\times$

friction can be avoided, and thus, relatively fast propulsion can be achieved. When it is not initially aligned, it generates a torque to rotate till it aligns to the field gradient. An additional experiment was carried out to compare the effects of the threads. Different types of MagPieRs, shown in Figure 3, were compared. One (with thread) measured the average record at 14.8 ms from four different trials (the standard deviation was 4.2 ms) while the other (without thread) took an average of 9.4 ms with 2-ms standard deviation. It should be noted that pure travel time between start and goal lines was measured to exclude the effect from collision to wall. It is evident that it takes more time to align the MagPieR with thread to the field gradient. Such deviation of measured time is attributed to the initial alignment condition.
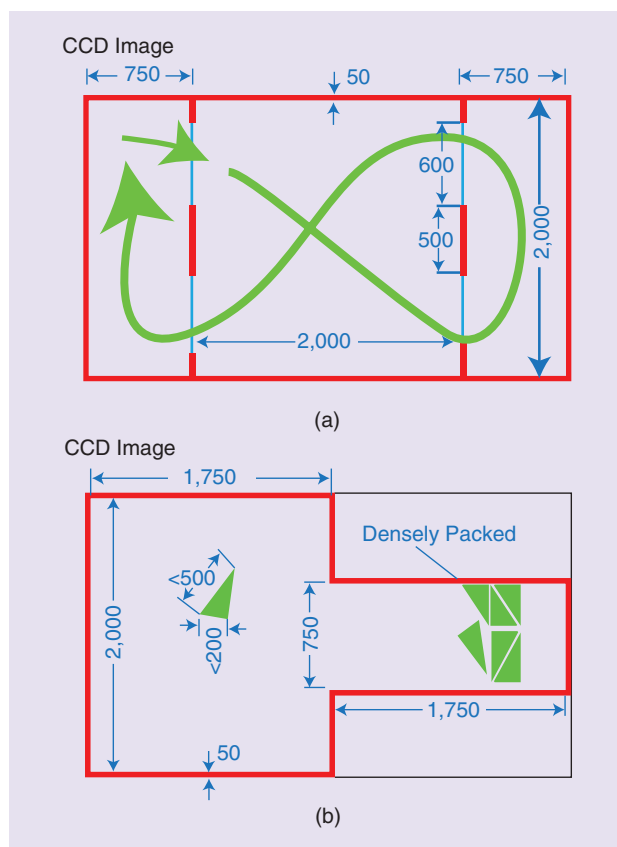

Figure 7. (a) The mobility challenge and (b) the microassembly task arenas in the 2011 MMC edition [15]. Dimensions are given in micrometers.

Finally, the propulsion performance of MagPieR was compared with other mobile microrobots in the competition. They represent the state-of-the-art mobile microrobots in air (Table 1). When compared with other propulsions of mobile microrobots, the combined driving of MagPieR and the optimized coil setup with magnetic core showed a much higher propulsion performance in terms of velocity. The demonstrated velocity (71.4 mm/s, 178.5 body lengths/s) was four times higher than that of the next competitor, Mag-μBot, which used large Helmholtz coils that lost their magnetic field intensity from the distance. The EMMA system consisted of externally actuated coils and magnets under the surface, whose inertia prevented higher speeds. MiniMag was a redoubtable competitor with its optimized eight pairs of soft magnetic core coils. However, it chose to operate the microrobot in a liquid environment, whose viscosity prevented high dynamics but privileged extremely precise actuation. With a fine visual servoing control, MiniMag bagged the first prize on the microassembly task. It should be noted here that the comparison with other nonparticipating mobile microrobots did not allow us fair comparison simply due to the scale difference and nonstandard arena.

> **Combining different physical effects is a promising key for the future of highly dynamic mobile microsystems and associated applications in micromanipulation, microassembly, or minimally invasive surgery.**

Microrobotics Challenge Got Stronger in 2011 at the Fifth MMC Edition

Similar to its previous edition, the MMC 2011 Challenge was held with the well-known IEEE ICRA in May 2011 in Shanghai. The maximum allowed dimensions of the microrobots fitted the 600-μm sphere, but the organizers changed the rules of the challenge. Qualification videos showing some basic actuation were no longer considered but required performing a fixed distance very similar to the 2-mm dash task. When compared with the past contests, the number of events was reduced to two, while the overall level of complexity was increased. The freestyle task was suppressed. The new tasks were as follows:

- The mobility challenge, replacing the 2-mm dash, was the new speed event where the microrobot must navigate through a planar track as fast as possible [Figure 7(a)].
- The microassembly event, where the microrobot must assemble multiple triangular-shaped microcomponents into a narrow area, simulating a channel [Figure 7(b)].

The first event was intended for testing not only the speed but also the microrobot's fast maneuvering agility,

while the microassembly task was simulating precise manipulation operations, such as within a human blood vessel.

A total of 11 teams registered, of which seven teams were squared off in Shanghai this year, with new entrants from the University of Hawaii, University of Texas at Arlington, University of Maryland, and the Italian Institute of Technology, and veterans from UW, the Stevens Institute of Technology, and finally, the CNRS France.

The MagPieR microrobot team successfully competed this year with an upgraded system featuring vision-based feedback control. The mobility task record was set to 1.86 s with an average time of 2.2 s, enabling theMagPieR microrobot to again reach first place. As perspectives, we noticed that with further optimized control laws, the MagPieR's feedback dynamics and precision might be significantly enhanced using a combination of continuous and impulse driving. Other works include exploring the liquid environment.

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Given the continuous technology advances and microscale requirements, the MMC contest will gradually gain technical complexity as well as popularity. Further advances are required in all fields, including propulsion methods, autonomy, power management, sensing, and control. In the future, the teams will face complex requirements, such as involving into multiagent tasks on real-life environments that prove harsh and challenging at this tiny scale.

In conclusion, when compared with the versatile centimeter-size miniature robots [2], we find that today's microbots still lack internal power sources and autonomy. The real microrobot concept probably depicts more of a mechanically active or even inert agent controlled wirelessly by external fields (mainly magnetic, electrostatic, and electromagnetic). Processing units and related sensors remain completely external. However, over the last decade, a net progress in terms of miniaturization, maneuverability, and task complexity is clearly noticeable. First commercial applications [16] in remote medical surgery and drug delivery are about to see the daylight. Micron-size robots could also solve some of the most important problems in micromanipulation at this scale. Attractive areas involve microcomponents assembly by means of wireless agents, which are expected to emerge in the next few years.

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