Motion Control at the Nanoscale

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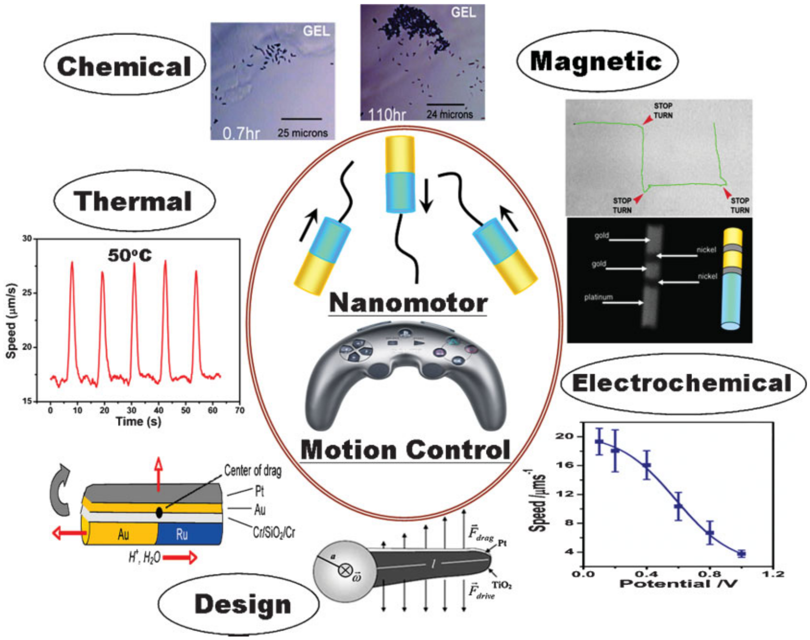

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Synthetic nanoscale motors represent a major step in the development of practical nanomachines. This Review summarizes recent progress towards controlling the movement of fuel-driven nanomotors and discusses the challenges and opportunities associated with the achievement of such nanoscale motion control. Regulating the movement of artificial nanomotors often follows nature's elegant and remarkable approach for motion control. Such on-demand control of the movement of artificial nanomotors is essential for performing various tasks and diverse applications. These applications require precise control of the nanomotor direction as well as temporal and spatial regulation of the motor speed. Different approaches for controlling the motion of catalytic nanomotors have been developed recently, including magnetic guidance, thermally driven acceleration, an electrochemical switch, and chemical stimuli (including control of the fuel concentration). Such ability to control the directionality of artificial nanomotors and to regulate their speed offers considerable promise for designing powerful nanomachines capable of operating independently and meeting a wide variety of future technological needs.

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1. Why Motion Control?

The use of synthetic nanomotors to power nanomachines and nanofactories is one of the most exciting challenges facing nanotechnology. Designing and building new and powerful nanoscale motors and propulsion modes is the first challenge. This challenge has recently been covered in several excellent reviews.[1–4] The second important challenge is to keep the new nanomachines going in a steady direction and to steer and navigate them towards their destination. Such precise control of the motion of artificial nanomotors is essential for meeting the demands of future applications and complex operations of these nanoscale devices in diverse areas ranging from drug delivery to nanoscale assembly or patterning. However, the precise navigation of nanoscale objects is extremely challenging because of the combination of Brownian motion and low Reynolds numbers (where viscosity dominates). Accordingly, navigation principles used in the macroscale world are not applicable for nanoscale propulsion. Achieving such precise temporal and spatial motion control at the nanoscale, including fine tuning of the motor speed and cyclic ‘‘on/off’’ activation, thus requires innovative methods of regulating the motor activity or its fuel supply.

In this article we highlight various approaches to control the motion and regulate the speed of artificial nanomotors, particularly in chemically powered nanomotors. Since biological motors provide an inspiration to the design and operation of synthetic nanomotors, we examine first how nature regulates the motion of its biomotors. By understanding the controlled motion of natural biomotors we hope to be able to impart a precise motion control on artificial nanomotors towards the design of functional nanomachines conducting a wide variety of missions.

2. How Does Nature Regulate the Motion of its Biomotors?

Nanoscale biomotors rely on spontaneous reactions of energy-rich molecules, most commonly adenosine triphosphate (ATP), to generate mechanical movement and perform various biological functions. Such biomotors display amazing motion capabilities, with remarkable directional movement and speed regulation.[5,6] To overcome viscosity forces and Brownian motion, the muscle myosin and walking protein kinesin move along actin or microtubule protein filaments, respectively, which act as motor ‘‘tracks’’ or ‘‘highways’’ (Figure 1).[7] Kinesin and myosin thus take numerous steps along these filaments without dissociating themselves and rely on these interactions with the track filament for their directionality. Recent efforts aimed at coupling these protein motors with microscale engineering (synthetic) devices involved gliding of such filaments on motor-coated surfaces.[8] Advanced guiding concepts have been proposed for controlling the path along which the filaments glide. Topographical surface features and patterns (acting as ‘‘obstacles’’) have been used to provide precise spatial motion control within such synthetic devices.[8]

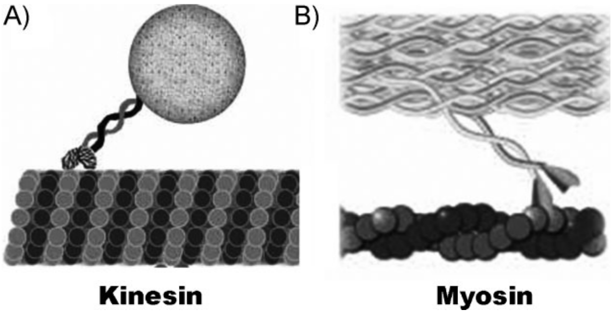

Figure 1. Controlled motion of the motor proteins kinesin and myosin along microtubule “tracks” and actin filaments, respectively.[7]

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In addition to directional motion, biological motors display remarkable speed regulation. Various parameters affect the biomotor activity and hence its speed, including the fuel (ATP) concentration, or the presence of ATP-regenerating or hydrolyzing enzymes, divalent cations, or inhibitors. Appropriate (bio)chemical stimuli can thus been used to regulate the motion of biomotors. For example, Hess et al.[9] described the use of light for controlling the movement of kinesin. This was accomplished by exploiting a UV-induced release of caged ATP combined with enzymatic ATP

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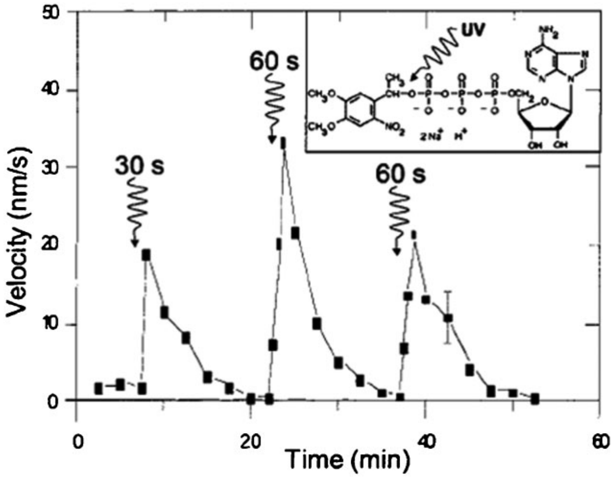

Figure 2. Average speed of microtubules (N=10) after exposure of caged ATP to UV light for 30, 60, and 60 s converting 20%, 30%, and 20% of the initial caged ATP into free ATP, respectively. The presence of the ATP-consuming enzyme, hexokinase, leads to a rapid decline of the microtubule velocity. The inset shows the structure of DMNPE-caged ATP. Reproduced with permission from Reference [9]. Copyright 2001, American Chemical Society.

degradation by hexokinase to turn the molecular shuttles ''on'' and ''off'' sequentially. Such light-modulated motion of kinesin is illustrated in Figure 2, with the corresponding increase and decrease in the velocity during repetitive light on/off cycles. Adding and removing inhibitors (such as the anesthetic lidocaine) can also be used to reversibly inhibit or restore the movement of kinesin or myosin on their microtubules or actin filaments.[10] Divalent cations such as Ca^{+2} and Mg^{+2} also influence the movement of myosin and kinesin, respectively, by inducing conformational changes essential for the motion.[11] In addition, living organisms display a directed motion towards a chemical attractant or a fuel-rich zone and away from toxins.

Another approach that nature uses to overcome Brownian motion and viscosity effects involves the use of asymmetric motion patterns, such as rotation of a helical-shaped structure. One of the best studied examples is the swimming locomotion of *Escherichia coli* bacteria, which spin their rotary helical flagellar motor counter clockwise for their cork-screw propulsion.[12] The binding of heavy metals to the rotor of the flagellar motor impairs its motion instantaneously. For example, rapid halted and resumed motion of the flagellar motor of the *S. marcesens* bacteria was illustrated in the presence of copper ions and the ethylenediaminetetraacetic acid (EDTA) chelating agent, respectively.[13] A thermal (on/off) modulation of the enzyme-based biomotor (F1-ATPase) was reported through a temperature-induced formation and collapse of the supramolecular nanomesh.[14] In an another report, on and off rotation of F1-ATPase-based nanopropeller was accomplished in the presence of ATP and sodium azide, respectively.[15] Such remarkable motion-control capabilities of biological motors provide inspiration and guidance for controlling the movement of synthetic nanomotors and for imparting greater sophistication to the motion of such man-made nanomachines.

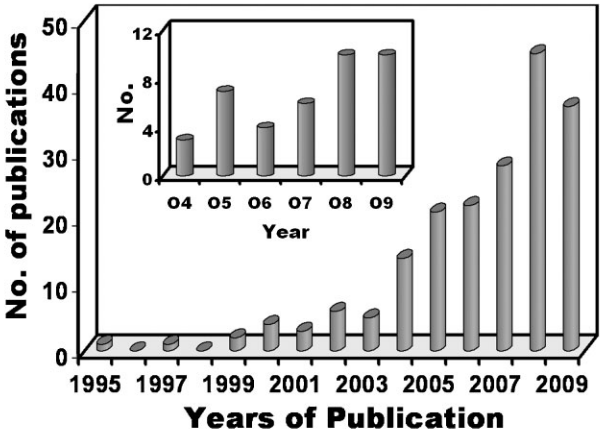

Figure 3. Analysis of the publications of nanomotors, including both biomotors and synthetic motors, over the 1995–2009 period (up to early October 2009). Inset: analysis of the publications of catalytic (chemically powered) nanomotors.

3. Catalytic Nanomotors

The quest for functional nanomachines has stimulated the development of artificial nanomotors. Such growing interest in the field of nanomotors is reflected from the rapidly increasing number of publications dealing with biological and synthetic nanomotors during the 1995 to October 2009 period (Figure 3). Synthetic nanomotors may tolerate a more diverse range of conditions than biological machines to offer considerable advantages in the development of complex nanomachinery.[16] Yet, regulating the movement of artificial nanomotors may follow nature's elegant approach to advanced motion control. While there are several types of synthetic nanomotor, this Review focuses on the motion control of chemically powered catalytic nanomotors. Our goal is not to review the design or propulsion mechanisms of such nanomotors (as these were covered by several excellent reviews[1–4]) but to focus on the challenges of controlling and regulating the movement of such artificial motors, and on nanoscale motion control, in general.

The self-propulsion of macroscale objects in the presence of a peroxide fuel was demonstrated first by Whitesides's group in connection to the spontaneous movement of centimeter-scale polymeric (PDMS) ''boats'' with catalytic platinum strips on their stern at air–water interfaces.[17] Whitesides's experiment provided inspiration to creative efforts at Penn State University (USA) and the University of Toronto (Canada) that led to chemically driven nanoscale locomotion. This activity resulted in the continuous autonomous non-Brownian movement of bimetal (Au/Pt, Au/Ni) nanowires (Figure 4A) propelled by electrocatalytic decomposition of hydrogen peroxide fuel.[20–22] Subsequent efforts at Arizona State University and the University of California San Diego resulted in a dramatic acceleration of catalytic nanowire motors by tailoring the composition of the motor or the fuel.[18,19] Other promising fuel-driven nanomotors introduced over the past year have led to more complex and advanced motor structures, including a catalytic rolled-up tubular microjet engine from Mei's group (Figure 4B),[23,24] an asymmetric platinized-silicon

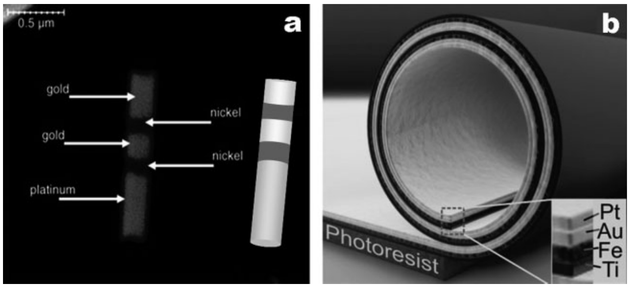

Figure 4. Schematic representation of a metallic nanowire (a) and catalytic rolled-up tubular microjet engine (b).[22,23]

microsphere from Zhao's team,[25] and porous (large surface area) bimetal nanowires from Ozin's group.[26] The improvements in the power and efficiency of bimetal nanowire motors have facilitated the pickup and transport of ''heavy'' cargo, such as large microspheres, and indicate promise for carrying out different payloads.[27,28] Such developments may lead to a wide variety of exciting applications of artificial nanomotors, including nanoscale assembly and transport, microfactories, microscale actuation, drug delivery, nanoscale surgery, and motion-based biosensing. The rapid and impressive recent growth of the activity in such catalytic nanomotors, since the early breakthroughs of Whitesides, Ozin, and Mallouk/Sen, is indicated from the publications analysis displayed in the inset of Figure 3.

Such challenging applications require precise spatial and temporal control of the nanomotor direction, a fine control of the motor speed, and innovative strategies for generating complex movement patterns. For example, future cargo transport and distribution applications of nanomotors would require the ability to stop the motion of the nanomotor at predetermined locations and to resume it repeatedly on demand in connection to successive cargo loading and releasing steps. Similarly, the integration of nanomotors into microchip systems will require precise directional movement for navigating the motors along predetermined complex paths (''traffic lanes'') or sorting them within the intersections of microfabricated channel networks.

The ideal control system would thus regulate the motion of the nanomotor over defined times and defined locations along specified trajectories. Precise control of the nanomotor speed (over a wide range of speeds), as well as a rapid and repetitive on/off switches, are thus highly desired. Yet, a practical ''braking system,'' providing an on-demand stopping power (to oppose the force provided by the motors), remains a challenge. Similar to train engines, it is preferred to reduce the activity of the motor to slow it down gradually prior to stopping it, rather than suddenly applying the brakes fully while the motor running at full speed. In addition to an on and off button and to a controlled speed it is desirable to have a ''reverse'' switch to return the motor to the starting point upon completing a mission or to repeat a given task. In the following sections we discuss recent advances towards controlling the motion and regulating the speed of catalytic nanomotors and for achieving complex movement patterns.

3.1. Magnetic Guidance of Catalytic Nanomotors

Magnetically directed movement of nanowire motors has been accomplished through the incorporation of a ferromagnetic (nickel) segment that can be magnetized by an external magnetic field (Figure 4A).[22,28] Nickel segments that are shorter than their diameter could thus be magnetized transversely rather than longitudinally. This allowed a precise magnetic guidance and steering of the catalytic nanowire motors by controlling the orientation of an external magnetic field, that is, orienting their net magnetic moment parallel to the field.[18] It should be emphasized that the magnetic field only orients the nanowires and is not driving them or altering their speed. However, modulating between weak and strong magnetic fields can be used to initiate and stop the motion, respectively. Repetitive ''stop-and-go'' and ''stop-turn-and-go'' operations, with high spatial and temporal resolution, have been illustrated (Figure 5).[28]

The ability to use magnetic motion control to steer catalytic nanomotors towards their destination was illustrated in complex microchannel networks.[28] Such magnetic navigation involved a directed motion of chemically powered Au/Ni/Au/Pt-CNT nanowire motors through pre-determined paths of a polymeric microchannel network, along with selective sorting in the microchip intersections. Such ability of a nanomotor to

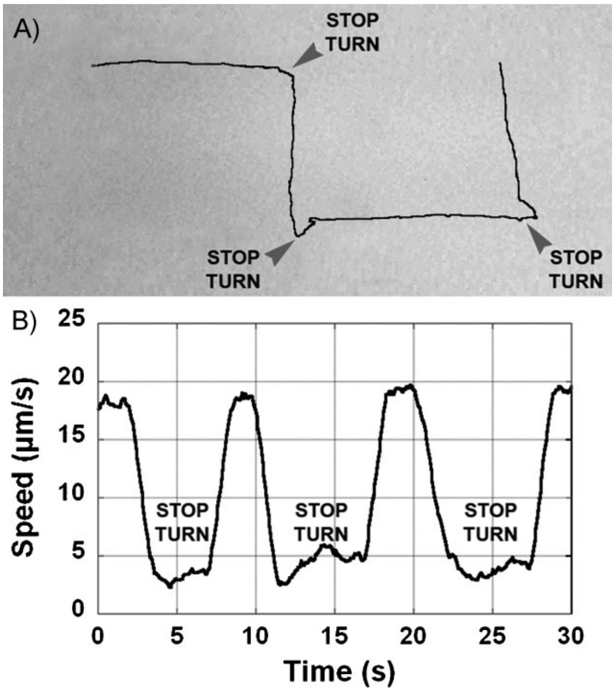

Figure 5. ''Stop-turn-and-go'' nanomotors. Static image (A) and the corresponding speed profile (B) of the stop-turn-and-go nanomotor under an oscillating magnetic field. Stop–Turn labels denote where the nanomotors are stopped for ≈5 s and the magnetic field is rotated by 90°. All motions are in the presence of 2.5 wt% H_2O_2 solution. The magnetic field is oscillated by modulating the distance of an external magnet from the nanomotors-containing microslide between ≈10 and 1 mm for the go and stop motions, respectively. Reproduced with permission from Reference [28]. Copyright 2008, American Chemical Society.

travel on a pre-determined channel path is an important aspect of integrating nanomachines into microfluidic networks towards the design of advanced microsystems.

Magnetic guidance has also been applied recently to catalytic tubular microjet motors.[23] As illustrated in Figure 4B, such catalytic engines are prepared by depositing a multimetallic thin film onto a flexible substrate that is rolled up to form an open conical microtube with an inner catalytic platinum layer. This design offers high speeds corresponding to 50 bodylength s^{-1}, with the peroxide fuel entering through the front end of the jet engine tube, while the internally generated oxygen bubbles depart from the wider opposite end. Such simple layer engineering and tube shape offers control over the directional movement. The incorporation of a ferromagnetic (Fe/Co) layer into the tube wall enables magnetic remote control of the motility direction of the catalytic microjets. Moving trajectories, which can be controlled by applying a rotating magnetic field (e.g., circular motion) have thus been visualized directly by long microbubble tails.

3.2. Tailored Design Towards Rotational Motion

While magnetized nanowires have been used for precise directional motion control,[18,22,28] more complex movement patterns are essential for a variety of demanding nanoscale applications. Various groups have addressed the challenge of rotational motion of catalytic nanomotors by imparting an asymmetric character onto bisegment nanowires in a peroxide fuel bath.[21,29–33] Ozin's group[21] reported on the rotational behavior of synthetic bimetal (AuNi) nanowire rotors anchored to a silicon wafer. Control of the angular velocity of the rotating wires was accomplished by varying the hydrogen peroxide concentration and the length of the nickel segment. Mirkin's group[29] demonstrated the ability to control the asymmetric forces involved in fuel-driven catalytic nanomotors by exposing only one side of the catalytic metal segment with the catalytic material. Similarly, Zhao's group[30] demonstrated the ability to control the asymmetric forces involved in fuel-driven catalytic nanomotors by coating one face of Si nanowires with the catalytic material (Pt and Ag). Mallouk and Sen[31] demonstrated a different approach for imparting the asymmetric character essential for rotating catalytic nanomotors. They used a trimetallic (AuRuPt) nanorotor and demonstrated ultrafast rotation through added perpendicular force generated along two axes (Figure 6A). Gibb and Zhao[32] reported a multicomponent rotational nanomotors consisting of Pt-coated TiO_2 nanoarms grown on silica microbeads designed by dynamic shadowing growth (DSG), which rotate about an axis through the center of the microbead and perpendicular to the TiO_2 arm (Figure 6B). Catchmark et al.[33] demonstrated rotational movement in a conventionally microfabricated microgear based on the catalytic reactions in hydrogen peroxide on the Au/Pt surfaces.

3.3. Thermally Controlled Motion of Catalytic Nanomotors

We demonstrated recently a novel approach for modulating and activating thermally the motion of catalytic nanomotors over defined times.[34] PtAu nanowire motors exposed to elevated temperatures (40–70 °C) traveled substantially longer distances than the room-temperature motors over the same time period (e.g., average distances of 45 versus 14 μm over 1 s at 65 °C and 25 °C, respectively). This was accomplished by placing the heat source (a 25-μm-diameter Au-coated Pt wire) about 30 μm above the plane of the nanomotors. Such heat-induced acceleration reflects changes in the kinetics of the redox processes of the peroxide fuel and of the solution viscosity. Temperature-dependent electrochemical processes are well established and have been exploited earlier for improved electroanalytical measurements in connection to "hot-wire electrochemistry."[35] Exposure of the PtAu nanomotors to localized heat pulses led to a highly reversible and fast thermally modulated motion (Figure 7), with a sharp increase and decrease of the velocity during repetitive temperature-induced "fast/slow" cycles. The thermally regulated motion was also combined with magnetic guidance towards a more advanced temporal and spatial motion control. Such combination of heating pulses with a directional magnetic control could allow coupling of the thermally accelerated motion with magnetic steering at different directions at preselected times and locations, and would facilitate the loading and unloading of cargo over defined locations.

3.4. Electrochemically Triggered Motion

We illustrated an electrochemically controlled movement of catalytic nanomotors, including a cyclic on/off switching of the motion of catalytic nanomotors and fine tuning of the motor speed through control of the applied potential.[36] Such electrochemical control of the nanomotor movement was accomplished by placing a gold wire electrode in close proximity (≈150 μm) to the nanomotors and applying positive or negative potentials to induce oxidation or reduction reactions of the peroxide fuel or dissolved oxygen, respectively. The ability to use applied potentials to control the nanomotor speed is illustrated in Figure 8. For example, stepping the potential from −0.4 V to different positive potentials leads to a gradual decrease of the speed from nearly 20 μm s^{-1} to 16, 10, and 4 μm s^{-1} (at +0.40, +0.60, and +1.0 V, respectively (Figure 8A)). Similarly, stepping to different negative potentials (from an initial value of +1.0 V) results in a gradual rise in the speed

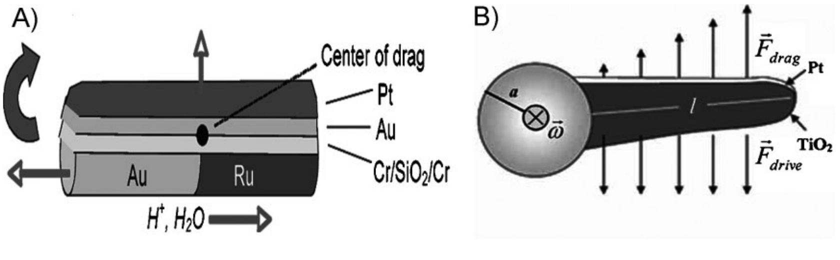

Figure 6. Schematic drawing of the structure and force analysis of newly designed rotary nanomotors based on A) trimetalic Au-Ru-Pt nanowires and B) Pt-coated TiO_2 nanomotors.[32] Reproduced with permission from Reference [31]. Copyright 2009, American Chemical Society.

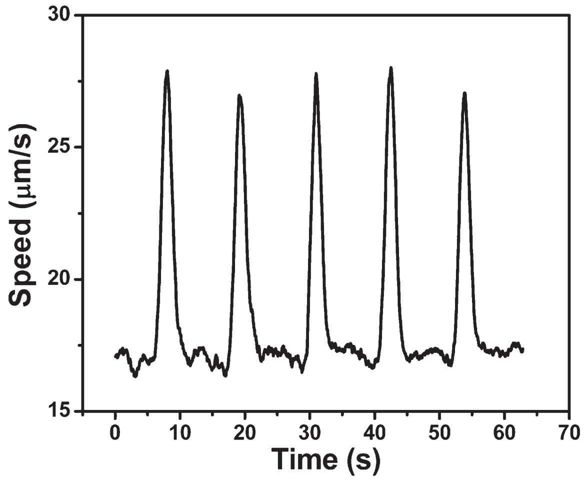

Figure 7. Modulated motion of catalytic nanomotors during five 1.5 s heat pulses (corresponding to a temperature of 50 °C) at 11.5 s intervals. Data shown represent the average speed of 3 nanomotors. The elevated temperature was obtained by using a heat current of 700 mA with the Au wire located 35 μm above the plane of the nanomotors.[34]

from 4 $\mu m\,s^{-1}$ to 8, 12, and 16 $\mu m\,s^{-1}$ at −0.10, −0.20, and −0.30 V, respectively (Figure 8B). Such potential-induced motion control has been attributed primarily to changes in the local oxygen level (generated and consumed at the positive and negative potentials, respectively). Cyclic on/off switching could thus be accomplished using 10 s square-wave potential pulses of −0.40 and +1.0 V (versus a Ag/Ag/Cl reference), with the positive potential serving as the braking system while the negative potential is used to trigger and accelerate the motion. Dramatic speed acceleration, from 4 to 22 $\mu m\,s^{-1}$, was thus observed upon stepping the potential from +1.0 to −0.40 V. Such reversible voltage-driven motion represents an attractive approach for on-demand regulation of the speed of artificial nanomotors. Ultimately, this redox-switchable motion strategy could be combined with networks of individually addressable microelectrodes that would guide the speed and direction of catalytic nanomotors along their path (through modulation of the local fuel level).

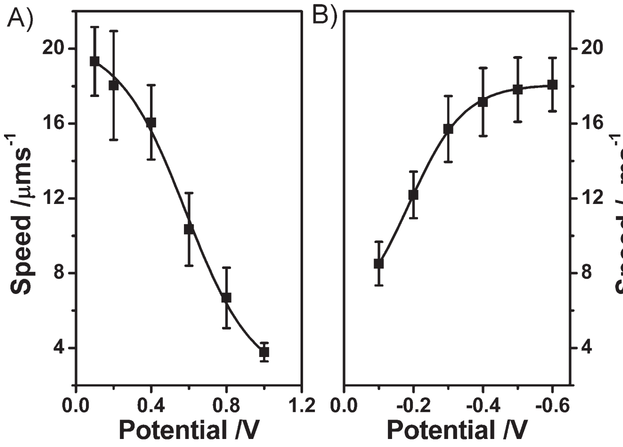

Figure 8. Speed-potential profiles of AuPt nanomotors in a 5% H_2O_2 solution. Nanomotor speed upon A) stepping the potential from −0.4 V to different positive potentials (0.1, 0.2, 0.4, 0.6, 0.8 and 1.0 V) and B) stepping the potential from +1.0 V to different negative potentials (−0.1, −0.2, −0.3, −0.4, −0.5, and −0.6 V). Reproduced with permission from Reference [36]. Copyright 2009, Royal Society of Chemistry.

3.5. Chemically Controlled Nanomotor Movement

As discussed above (in Section 2), nature's biomotors often rely on various (bio)chemical stimuli for regulating their motion. Similarly, the motion of catalytic nanomotors can be regulated through chemical stimuli or control the fuel level. In particular, a dramatic acceleration of PtAu nanomotors, from 10 to 52 $\mu m\,s^{-1}$, was observed recently upon adding 100 μM silver ion to the 5 wt% peroxide fuel solution.[37] Such silver-induced acceleration has been attributed to the underpotential deposition (UPD) of silver on the AuPt nanowires that leads to differences in the surface and catalytic properties. The defined dependence of the motor speed upon the Ag(I) concentration was exploited to develop a new motion-based silver sensing protocol. Hydrazine is another fuel "additive" that can influence the nanomotor movement. A dramatic acceleration of catalytic nanomotors (Au/Pt-CNT), from 50 to 94 $\mu m\,s^{-1}$, has been accomplished by adding hydrazine to the hydrogen peroxide fuel.[18]

As expected, controlling the fuel level has a profound effect upon the nanomotor speed. The speed was shown to increase linearly with the level of the hydrogen peroxide fuel over the 2.5–10 wt% range.[18] Catalytic nanowires motors display a chemotactic behavior in the presence of a gradient of the fuel concentration, with a directed movement and increased speed toward a zone with higher peroxide concentrations.[38] Such behavior resembles the movement of living organisms toward a chemical attractant or away from a reactant.[39,40] Controlling and modulating the local fuel level may thus be used for guiding, initiating or slowing the motion of chemically driven nanomotors. In the first example of chemotaxis in a non-living system, Sen's group[38] illustrated how PtAu nanowire motors can propel themselves along a gradient of hydrogen peroxide (diffused in water) toward a region with a higher fuel concentration. Figure 9 shows the chemotactic movement of such nanomotors towards a hydrogel (agarose gel) containing 30% aqueous hydrogen peroxide. Such chemotactic motion leads to the accumulation of more than 70% of the wires at the gel within 110 hours (as indicated from images on top). The chemotaxis of PtAu nanomotors arises from the active diffusion by the combination of electrokinetic translation and the Brownian rotation (which makes the movement appear to be a random walk).

Ultimately, it is desirable to develop completely autonomous and intelligent "smart" nanomotors that constantly gather information about their surrounding environment, and co-operate to make "decisions" and navigate from point A to point Z. Such autonomous self-navigated nanomotors would operate independently and perform a wide range of challenging tasks with minimal or no remote human intervention. One approach that we are currently exploring for designing such self-controlled smart nanomotors is based on enzyme-logic-controlled motion. This involves the use of multiple (bio)-chemical inputs (substrates, enzymes, inhibitors), received from their surrounding environment, logically processed by a

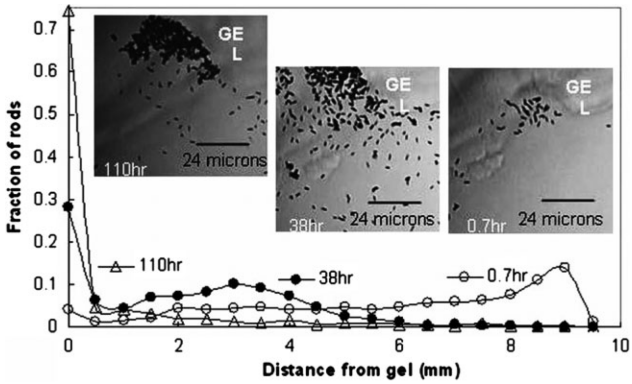

Figure 9. The changing distribution of PtAu nanomotors in a concentration gradient of a H_2O_2 fuel. The gel (soaked in 30% H_2O_2) appears in the upper part. The images were taken at different times: 0.7 h, 38 h, and 110 h. The fraction of rods was evaluated by dividing the number of rods in a frame at a certain distance by the total number of rods summed up from the frames at all the distances. The insets show the change in population of PtAu nanowires near the gel, visualized with bright-field inverse microscopy at 50× magnification. Reproduced with permission from Reference [38]. Copyright 2007, American Physical Society.

biocomputing (logic gate) system to yield a final YES/NO signal based on the specific pattern of biochemical signals. Guided motion through microchannel networks could also be achieved through a localized immobilization of peroxide-consuming enzymes (e.g., catalase, peroxidase) at specific channel sections of such networks, that is, tailoring the local fuel concentration.

3.5.1. Collective Behavior

So far we have discussed the directionality of isolated nanomotors. The design of smart nanomotors goes beyond such individual motors and involves the co-operative action of multiple motors. Future multinanomotor networks will rely on their collective behavior, where each motor senses its environment (including chemical ''signals'' from its neighboring motor), processes the information gathered, communicates with others, and takes a proper action in response. Such interactions between individual motors and their environment should lead to different collective motion patterns and potentially to a group movement. It would also help moving in groups without bumping into each, that is, keeping the traffic flowing and minimizing the risk of collisions or crashes. Understanding such interactions may lead to the design of nanoscale systems in which artificial motors could work co-operatively. Interactions (''communication'') among individual motors may also lead to their self-organization towards the realization of complex nanomachinary. In the first example of such interaction between catalytic nanomotors, Malouk and Sen[31] demonstrated different interactions between pairs of co- and counter-rotating nanowires. Co-rotating wires could thus approach each other only to a distance of $\approx 0.9\ \mu m$, although the precise mechanism of this interaction was not fully understood. In a recent effort the same group reported on light-powered autonomous AgCl micromotors in water that exhibit motor–motor interactions, including swarming and predatory–prey behavior.[41] Such ability to construct systems of synthetic particles that can interact over relatively long distances indicates promise for creating ''intelligent'' synthetic nano/micromachines that function collectively.

4. Conclusions and Outlook

We have reviewed recent research activities aimed at controlling the motion of catalytic nanomotors and discussed the challenges and opportunities associated with the achievement of such precise nanoscale motion control. A summary of such strategies for directing the movement and controlling the speed of artificial nanomotors in connection to various stimuli is given in Table 1. Understanding the remarkable underlying principles of the motion control of nature's remarkable biomotors has provided researchers with new insights into how to impart greater sophistication onto the movement of artificial nanomachines. A variety of approaches for imparting precise motion control onto artificial nanomotors and for

Table 1. Motion control in catalytic nanomotors.

Type of Motion Control	Function/Operation	Design	Comments	Reference
Magnetic (using Ni segment)	Magnetic guidance	Nanowires	Directionality	[22]
	Directional motion in microchannels, cargo pickup, "stop/turn/go"	Nanowires	Magnetic navigation within complex channel networks and sorting in intersections	[28]
	Control over faster nanomotors	Nanowires	Control and directionality by modulating the strength of a magnetic field	[18]
Magnet (using Fe segment)	Motion control, turn and rotate	Rolled-up microtubes	Multimetallic thin film of Fe used for a remote magnetic control; bubble mechanism	[23,24]
Thermal	On-demand thermal acceleration with and without magnetic guidance	Nanowires	Use of localized heat pulses for thermally modulating the speed	[34]
Electrochemical (Potential)	Cyclic "on/off" activation and fine motion control	Nanowires	Use of electrolytic reactions of the fuel constituents (under potential control) for starting and stopping the motion reversibly	[36]
Concentration gradient	Chemotaxis, through active diffusional motion toward higher fuel concentration	Nanowires	Accumulation of nanomotors within a peroxide-rich gel	[38]
Asymmetric structure	Rational design (clockwise and counter clockwise rotations)	Nanowires	Imparting an asymmetric character onto bisegment nanowires led to rotational motion	[21,29,31,33]
Asymmetric structure	Rotational motion	Nanoarms	Pt-coated TiO_2 arm on silica microbeads by DSG	[32]

modulating their speed temporally and spatially have been discussed. Other stimuli, such as light,[9,41] may also be used for controlling the motion of nanomotors. Magnetic control of fuel-free ''flagella-like'' nanomotors has also shown great promise for advanced motion control at the nanoscale.[42,43] These non-catalytic nanomotors are beyond the scope of this review but their propulsion may be coupled with catalytic motor in a ''hybrid'' type fuel-efficient design.

The ability to guide the motion of catalytic nanomotors and to precisely control their speed indicates great promise for generating on-demand complex movement patterns. These accomplishments are only the first step towards the design of functional and sophisticated nanomachines, performing diverse tasks and demanding activities. We expect that such developments will eventually lead to autonomous integrated highly maneuverable nanomachines, capable of operating independently and performing a wide range of demanding tasks, including nanoscale assembly or patterning, drug delivery, and nanosurgery. There are still major challenges to be resolved towards generating more complex nanomotor movement patterns, for providing an on-demand stopping power, and eventually for designing self-regulated machines that sense their environment, make their own decisions and communicate with each other.

While the focus of this article has been on controlled motion of catalytic nanomotors, similar concepts could be applied for regulating the movement of other artificial nanomotors, for example, magnetic propellers.[42,43] Accordingly, we hope that this article will stimulate other teams to bring their particular expertise to address the challenge of precise control of the motion of artificial nanomotors and to accelerate the pace of developing functional nanomachines and complex nanomachinary for meeting future technological needs. Given the interest and the competitive cutting-edge research in this field, we anticipate exciting new ideas and applications in the future.

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biomotors · motion control · nanomachines · nanomotors

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