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Nanorobot Movement: Challenges and Biologically inspired solutions

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Abstract:

Nanorobotics is the technology of creating machines or robots of the size of few hundred nanometres and below consisting of components of nanoscale or molecular size. There is an all around development in nanotechnology towards realization of nanorobots in the last two decades. In the present work, the compilation of advancement in nanotechnology in context to nanorobots is done. The challenges and issues in movement of a nanorobot and innovations present in nature to overcome the difficulties in moving at nano-size regimes are discussed. The efficiency aspect in context to artificial nanorobot is also presented.

Keywords: Nanorobots, Nano-Swimmers, Diffusion, nanoparticle; Brownian motion; System Modelling

1 Introduction

The nanomanipulations of micro/nano-sized objects with nanometer precision using large equipments like atomic force microscopes is possible [1-2]. Scientists and engineers have shown a great interest to conceptualize, model, analyze and make nano-sized robots [3-7]. The prime reason for advancing attempts in the field of nanorobotics are the unique applications of the nanorobots in medical, health care and environmental monitoring, which are attributable to the size of nanorobots comparable with biological entities. In this context, there is an all-around development and ever-growing literature in nanotechnology which includes nanofabrication, nanoelectronics and quantum computing, nanomaterials and nanomachines etc. The attempts of making nanojoints and nanostructure [8] using carbon nanotubes (CNTs), the ‘single molecule car’ [9] using buckyballs as wheels, synthesis of rotary single-molecule motor driven by chemical [10] or optical [11] energy, fixing of ATPase to substrate used to rotate metallic or organic nanorods [12-13] and construction of nano sized artificial swimmer on the basis of a supermagnetic elastic filament [14] are some of the developments towards making nanorobots/ nanomachines.

The feasibility of nanomachines or nanorobots is inspired by existence of organisms and biologicals at same size scales performing very efficiently, in robust manner and intelligently. In realization of nanorobots, the challenging issues are increased apparent viscosity of surrounding medium [15], wear and friction [16], significant Brownian motion due to thermal agitation [17-19] and non-rigid nature in nano-size regimes [20]. Also for nanorobot, walking or crawling are difficult in comparison to flying and swimming. With very low Reynolds numbers, most of the nanorobots with flexible links are going to swim in fluids in stokes regimes [21]. Inertia is irrelevant and motion is instantaneous, not affected by past. Time makes no difference i.e. whether configuration are changed quickly or slowly, the pattern of motion is exactly same implying swimming by reciprocal motion is not possible. Biology has a large number of concepts and solutions ranging from active polymerization of gel networks [22], molecular motors moving on tracks formed by protein filaments [23] and rotating or beating cilia or rotating flagella [24, 25].

Diffusion (random walk) due to thermal agitation (Brownian motion) appears to be an important mode of propulsion in the size range below 600 nm to move small objects in fluid at room temperature [21, 26-27]. Eukaryotic and Prokaryotic cells have different mechanisms to utilize diffusion and elasto-hydrodynamic interaction of rotating or beating cilia or flagella to move in nano-regimes [28-33]. All through literature, it is established that finite stiffness or non-rigidity of beating filament, for example in eukaryotic cells like mammalian sperms, is crucial in motion. The non-rigidity of nanomechanisms has been captured by bead spring models [20], slenderness theory, Kirchoff’s-rod theory and a combination of resistive-force theory [34-36]. A review of the physics of fluids in nano-domains has been discussed as parameterised by various dimensionless numbers like Reynolds, Peclect, and Capillary etc. [37]. Noteworthy discussion in the aforementioned literature is that at low Reynolds number, a low Peclect number warrant that swimming will do no good till the swimmer outruns diffusion. In order to outrun the diffusion, the convective motion due to swimming is enhanced beating cilia or flagella more vigorously.

The present work traces the developments in context to realization of nanorobots. The achievements and human steps in nano-domains are compiled in section 2. The discussion on the various issues in nanorobot movement is presented in section 3. The innovations by biologicals to overcome the challenges posed to a controlled motion due to small sizes are given in section 4. In section 5, the efficiency aspect of nanorobot movement is discussed in context to future work.

2 Human Steps towards Realization of Nanorobots

In the endeavor to realize a nano-sized reprogrammable, multifunctional manipulator designed to move nano-sized parts or specialized devices through various programmed motions for the performance of a variety of tasks, the science and technology has to advance on many fronts like fabrication, electronics and controls, materials, mechanisms, computations etc. In the last two decades, there has been clear impregnation of humans in nano-sized domains with advancement in all these fields. The noteworthy progress marking the first few human steps in nano-domains are mentioned below.

2.1 Nanofabrication

The advent in nano-domains is enabled by advancement in nanofabrication technologies. In literature, the nanofabrication has been clubbed under categories namely direct, indirect and self-assembly [52]. Among direct methods, optical lithography (including extreme UV lithography and nanoimprint lithography), Electron beam lithography (EBL), Scanning probe lithography, Reactive ion etching and Focused ion beam (FIB) have emerged as important techniques in nanofabrication. The minimum feature sizes achievable on substrate in each of these techniques are tabulated in Table 1. Indirect methods like etched side wall deposited structures are capable of increasing the line structure density up to two times with size of line as low as 35 nm. Molecular self-assembly or bottom-up approach is the ultimate patterning technique and making of Carbon Nanotubes (CNTs) is a perfect example of self assembly technique.

2.2 Nanoelectronics

In the pursuit of miniaturization of devices, nanoelectronics is emerging as the technology maturing fast. The progress in nanoelectronics includes research and development under various categories as shown in Fig. 1.

Table 1 Different nanofabrication technologies and their size limitations

Fabrication Technology	**Minimum Achievable feature Size**
Optical Lithography	>30 nm
Electron Beam Lithography	4-5 nm
Nanoimprinting	~10 nm
Scanning Probe Lithography	~3 nm
Reactive ion etching	>50 nm
Focused ion Beam	>30 nm

The size reduction of electronic circuits, of the order of nanometres and below, is quintessential towards realization of autonomous, controlled and reprogrammable devices like nanorobots.

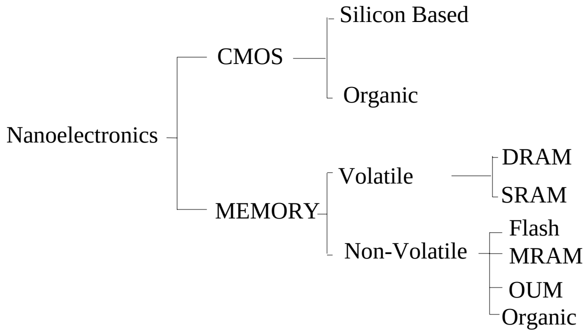

Fig. 1 Research and Developments in Nanoelectronics

The achievements like realization of 45 nm gate lengths in silicon based MOS technology and tremendous progress in non-silicon based nanoelectronics [53, 54] ensures that in near future, the controlled, autonomous nanorobots may be a reality. The technology in sub-50 nm is susceptible to short channel effects (SCE) and has triggered the research for SCE immune design strategies.

In this direction, extension of source and drain, aureole doping, retrograde doping, selection of metal gate, use of high-k and SOI structures, use of nanowires and Carbon Nanotubes (CNTs) with their superior current-voltage characteristics and high performance circuit applications has been modelled, fabricated and tested in the last decade [55-57].

2.3 Nanostructures, Nanomechanisms and Nanomachines

The construction of miniature nanomachines like nanorobots, is a goal of modern science and technology and the progress is inching towards the goal with achievements and milestones in the technology. Since the discovery of Carbon nanotubes [58], the progress in nanostructures and nanomechanisms has paced up to great extent. Nanotube tweezers [59] and nanotube linear bearing has been realized and demonstrated [60-61]. Nanojoints and various nanostructures using nanomanipulations of carbon nanotubes have been made [8] showing possibility of making a complex mechanism required for nanorobot. Recently a nanocar was made using fullerene structures exhibiting rolling motion on gold substrate [9]. While the engineers and physicists explore the top-down approach to nanoscale engineering through lithography and scanning probe microscope, chemists are working towards the goal by synthesizing molecular machines using self-assembly and bottom-up approach. The progress in construction of molecular motors [10, 11, 62-63] guarantees the availability of nanoactuators for motion of links and joints in nanorobots and nanomachines. The milestones towards making of a complete nanostructure mechanism of a nanomachine like nanorobot are tabulated in Table 2.

It is important to realize, however, that although it is often expedient in understanding nanomachines and nanomotors to make direct analogies to macroscopic machines, in answering fundamental questions regarding problems associated with friction, wear, transmission, efficiency, fuel, motion and work, such facile comparisons serve to cloud rather than simplify issues [63]. Some of the prominent issues and related problems concerned with motion in nano-domains are presented next.

Table 2 Chronology of Developments in Nanomachines and Nanorobots

YEAR	NANOPRODUCT	REMARKS
1985	Fullerenes [77]	Fullerenes are large, closed-cage, carbon clusters like C_{60} and C_{70}, and have several special properties that are not found in any other compound before.

1991	Carbon Nanotubes [58]	CNTs are extended nearly one-dimensional form of fullerenes with large length (up to several microns) and small diameter (a few nanometres). They possess extraordinary and interesting electronic, mechanic and molecular properties.
1994	Nanoshuttles [67]	Synthesis of a supramolecular structure (compound 1-[PF6]4) that can be reversibly switched between two states by proton concentration changes or by electrochemical means has been done. The super-molecule is a rotaxane comprising a molecular ring threaded on an axle containing two 'docking points'.
1995	Nanoturnstile [68]	Macrobicycle 1-3 have been prepared by palladium-catalyzed macrocyclization. The planar geometry of this system is such that the para axis of the inner ring exactly matches the inner diameter of the macrocycle. The inner ring rotates freely like spindle of a turnstile.
1996	Nanoswitches [66]	Dynamic control over molecular chirality was obtained by the interconversion of enantiomers of helically shaped molecules with either left or right circular polarized light (CPL).
1997	Nanorotors [64]	Photochemically bistable molecular rotor synthesis of cis-1a and trans-1b isomers of 2-(2,6-dimethylphenyl)-9-(2¢,3¢-dihydro-1¢H-naphtho[2,1-b]thiopyran-1¢-ylidene)-9 Hthioxanthene (1),being sterically overcrowded alkenes functionalized with an o-xylyl group as a rotor, is described.
1998	Nanoratchet [69]	The triptycene-substituted [3] and [4] helicenes 1 and 2 were examined as possible molecular versions of mechanical ratchets, where the triptycene serves as the

		ratchet wheel and the helicenes as pawl and spring.
1998	Molecular motor-Type I [72]	Transition to and from cis (same side) and trans (opposite side) on external excitation of groups across a double bond in a molecule
1998	Molecular Motor-Type II [73, 74]	The rings in complex structures of rotaxanes and catenanes are driven by chemical, electrochemical or photochemical means
1998	Nanogears [65]	A simple molecular gear has been demonstrated using Amide 1. At least 90% of the rotations about the Ar-CO bond in amide 1 are concerted with rotation about the C-N bond.
1999	Modified Molecular motor [11]	Repetitive monodirectional rotation around a central carbon-carbon double bond in a chiral, helical isomerization steps activated by ultraviolet light or a change in temperature of the system
2001	Molecular Elevator [70, 71]	Molecular elevator is composed of three rotaxane units interlocked mechanically and the charge of one of the two stations is sensitive to pH changes. As a result the platform can move between two levels by adding acid or base.
2003	Nanojoints [8]	Several kinds of nanotube junctions, the fundamental elements for both nanoelectronics and NEMS have been constructed by postioning the building blocks (CNTs) together and connecting them with naturally existing vander Waals forces, EBID or mechanochemical bonding.
2003	Molecular scissors [75]	Motion of photoisomerizable into an open-close motion of the blade moieties is reported.

2005	Nanocar [9]	Four Fullerenes based wheels performing rotary motion is achieved with integrated alkynes chassis structure.
2005	Nanoswimmer [14]	External magnetic field excitation to induce the beating of a supermagnetic filament attached to red-blood cell.
2006	Molecular pedals [76]	Change in molecular shape on cis-trans photoisomerization of an azobenzene unit is transmitted via a pivot point (a ferrocene unit) and a pedal like motion of large flat zinc porphyrin unit is achieved.

3 Issues and related problems in Nano-dynamics

Various scaling effects have been discussed in literature pertinent to motion of small-sized entities including synthesized particles and mechanisms and natural organisms. As the miniaturization results in a significant increase in surface to volume ratio, the small sized domains exhibit substantial surface phenomenon. In context to motion of nano-sized entities, some of the relevant issues and related problems are discussed below.

3.1 Viscosity in nano-domains

Viscosity is a physical property of fluid derived under the assumption of continuum. It represents the tendency of a fluid to undergo deformation when subjected to shear stress. A swimmer comprehends the resistive force due to viscosity of fluid during motion. [15]. When the length scale of fluid flow reaches close to size of molecules of the liquid, the underlying assumption that the fluid can be described as continuum is not valid. The “intrinsic” property of fluid viscosity shows a departure from classical behaviour. Viscosity is a measure of clingingness of molecules with adjacent molecules and imparts resistance characteristic to fluid against shear. As we go down the size scale, clingingness, being a surface phenomenon, becomes very significant exerting substantial resistance to shear and, thence, to motion past the fluid. Experimental evidence [44] on flows in molecular size channel below ten molecular diameters, of the order of few nanometres, shows that the fluid loses its liquid-like behaviour and assumes solid-like characteristics.

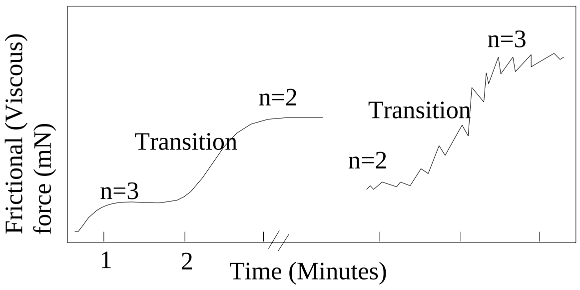

Fig. 2 Friction force between two parallel plates

The frictional force verses time of reduction of channel size adopted from [44] is shown in Fig. 2 where ‘n’ represents the number of molecular layers in the channel. It is clearly seen that as the channel is miniaturized, there is substantial increase in friction force due to viscosity. The “apparent” viscosity is 10^5 time the “classical” viscosity values [45]. One can imagine water behaving like glycerine in microchannels and like solid in nanochannels! The nanorobot in a microchannel will require more effort to move in comparison to moving in a macrochannel.

3.2 Friction in relation to miniaturization

During walking or crawling, friction plays a vital role. Friction, in classical sense, is governed by Amonton-Coulomb’s laws which state that sliding friction is (i) proportional to the normal load (ii) independent of the apparent area (A_a) of contact between the sliding bodies and (iii) independent of sliding velocity [46].

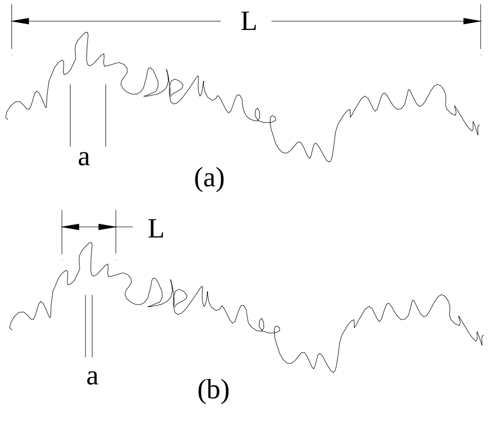

Fig. 3 Contact of rough surface and a smooth rigid surface with the apparent size of contact ‘L’ and average size of individual asperity contact ‘a’ in (a) Macro domains and (b) Micro domains

The classical interpretation of friction begins to err at micro and nano-size scales. The coefficient of friction in small size domains becomes size, load and velocity dependent [16, 47]. The apparent area of contact (A_a) and real area of contact (A_r) are close to unity in nano domains and resistance to sliding motion increases as real area of contact increases [48]

For constant size of contact and sliding velocity, the real area of contact is proportional to the normal load. The real area of contact changes with apparent contact size. The interfacial shear strength depends on the average size of individual asperity contact. The contact size ‘L’ and average asperity contact size ‘a’ are shown in Fig. 3. An increase in ratio of real-to-apparent areas of contact, normal load and sliding affects ‘a’ and, therefore, affects the interfacial shear strength and finally the coefficient of friction. For small contact size, load and sliding velocity, an increase of contact size and load or decrease of sliding velocity results in an increase of the coefficient of friction. However, with increased contact size and load or decreased sliding velocity, the scaling parameter reaches a critical value, and further change of contact size, load or sliding velocity does not affect the coefficient of friction, due to saturation of ‘a’ upon area of contact [49]. With the small size and low sliding velocity, for a nanorobot, walking and crawling, are challenging and difficult.

Under normal conditions, in a liquid, a Brownian particle will receive about 10^{21} collisions per second [50] and undergoes a kink in the motion with each collision. The reduction in ballistic motion due to random kinks reflects as *dynamical friction* to the motion of the colloidal particle as shown in Fig. 4 and has been modelled as Stokes drag in literature [17].

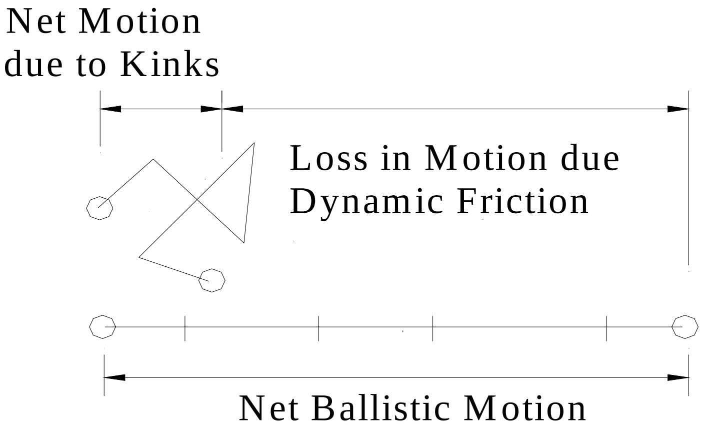

Fig. 4 Loss of Motion due to Brownian motion

Interestingly, motion and friction come from the same source – collision from the surrounding medium molecules. Nanomachines such as nanorobots working either in vacuum or in a fluid as mobile machines themselves become the size of the order of the Brownian particle, a nanoparticle free floating in the fluid. For nanorobots working in fluids, the thermal agitation around the machine influences its movement to a greater degree and will have to work against the substantial dynamic friction.

3.3 Non-rigidity in nano-domains

The concept of absoluteness in rigidity is debatable in nano-domains. It is possible to attain extremely high fundamental frequencies while simultaneously preserving very small spring constants in nano-domains [51]. It has been observed that the nano-structures/mechanisms have very low values of spring constant $(\sim 10\ N/m)$ and not infinite as in case of rigid bodies. The small values of spring constants make nano-mechanisms highly sensitive to forces and susceptible to appreciable magnitude of local deformations. It suggests that in nano-domains, local deformations affect overall motion to larger extent.

The physical nature of the model is hypothesized considering the non-rigid nanoparticle receiving only one impact from one surrounding medium molecule from some random direction. The nanoparticle being non-rigid will get deformed, i.e. the nanoparticle will be compressed at the impact site and bulge at the other end, resulting in a shift of the centre of mass. This is characterized as local motion of nanoparticle, as shown in Fig. 5(a). The nanoparticle will also move (get displaced) from its location due to the impact and finite values. This is characterized as global motion of nanoparticle, shown in Fig. 5(b). If the nanoparticle is considered as rigid, there is no local motion. In real time, a number of single impacts (surrounding medium molecule impacts) will take place on the nanoparticle

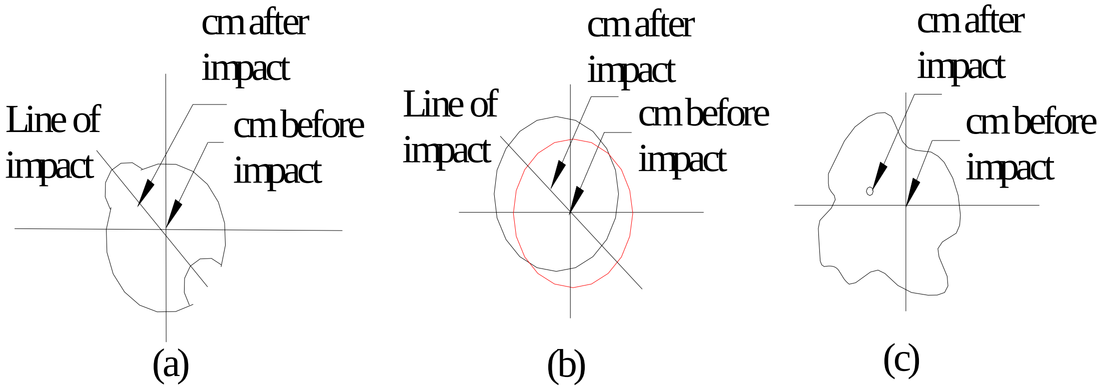

Fig. 5. Deformation and Motion of Nanoparticle (a) Local Motion due to Single Photon Impact (b) Global Motion (Rigid Body Motion) due to Single Photon Impact (c) Plausible Snapshot of Local Motion due to random number of random Impacts from random directions.

from all directions randomly. At any instant, a plausible snapshot of the deformed and moved nanoparticle is shown in Fig. 5(c). The centre of mass will get displaced due to local and global motions and the process will continue in time continuum. The motion of nano-structures/mechanisms which are non-rigid kind inherently is a synergism of local and bodily motion in nano-domains [17, 41].

3.4 Low Inertia in nano-domains

The very interesting aspect of motion of nano-sized entities is the negligible inertia. With low inertia and high viscous forces (refer 3 (i)) (the motion of nano-swimmer in fluid), the moving bodies in nano-domains swims in very low Reynolds number regimes. In the absence of inertial effect, time makes little difference towards contribution from inertial forces. In other words, whether nanoparticle/mechanism moves fast or slow, the pattern of motion is same [21]. The motion is instantaneous and there is little overshoot because of inertia properties. The absence of time effect is obvious in Navier-Stokes equation on neglecting inertial term. The NS equation:

$$-\nabla P + \eta \nabla^2 \vec{V} = \rho \frac{\partial \overline{V}}{\partial t} + \rho\left(\vec{V}.V\right)\vec{V} \qquad (1)$$

On neglecting Inertia terms it reduces to:

$$\eta \nabla^2 \vec{V} = \nabla P \qquad (2)$$

The control of motion seems to be easier as oscillations about set point or desired values may be absent. The overshoot of a nano-pendulum pass its equilibrium under natural conditions will be negligible and critical damping of its own devices may be possible. The major problem because of negligible inertia is that a nano-swimmer needs flexible or non-rigid oars to move forward. In case, the propulsion is done with single degree of freedom rigid oars, the motion is reciprocal during forward and backward stroke due to absence of time effects.

3.5 Low Peclect Number

At low Reynolds numbers, associated with nano-domains, it is difficult to mix the entities and the stirring motion/motion by convection is low in comparison to diffusion [37]. Convective motion will work only when Peclect number is more than unity, in any other case, sitting idle and getting diffused is as good as trying to move ahead by stirring or convective forcing.

The nano-bio-swimmers move a lot by convection but they must spend very large amount of energy in order to outrun diffusion. In order to make nanorobot move with energy efficiency, designer may need to consider diffusion instead of convection.

4 Nature's Innovation to move in nano-sized domains

The motion in biologicals in nano-domains has been studied extensively and is fostering research towards design and construction of nanorobots. The nature in the form of tiny biological entities has developed innovative mechanisms to counter the problems related to motion in nano-size domains. For example, nano-bio organisms prefer swimming or flying instead of walking or crawling to respond to significant adhesion or stiction in nano-domains. On the other hand, many cells are able to crawl on a solid substrate to which they stick using adhesive forces. This motion involves, in general, three processes: the formation and protrusion of a thin lamellipod in front of the cell, the adhesion of the lamellipod to the substrate, and its retraction at the rear, pulling the cell forward (Refer Fig. 6).

The formation of the lamellipod involves the polymerization of cytoskeletal filaments and their cross-linking near the membrane. Motion generation requires a symmetry breaking often associated with a tread milling of the cell cytoskeleton (the continuous asymmetric polymerization at the leading extremity of the gel and depolymerization at the rear). Typical examples for crawling cells are motion of fibroblast cells or fish epidermal keratocytes. In many other crawling cells, the cytoskeleton is an actin network and the motion generation involves a complex interaction between actin, myosin motors and many other proteins [78].

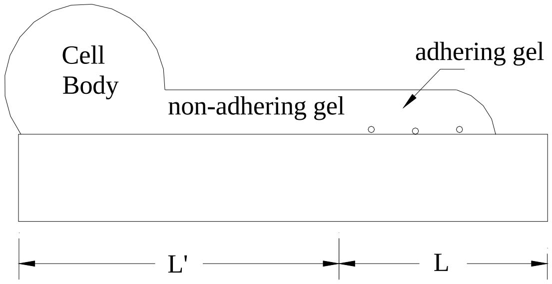

Fig. 6 Schematic representation of the advancing cell on a substrate

Mainly Biological movement is achieved by Biological motors [23], which convert chemical energy to effect stepwise linear or rotary motion. The word “motor” is used for proteins or protein complexes that transducer at a molecular scale chemical energy into mechanical work. Both rotary and translatory motors are known to exist and move in a deterministic way along a filament similar in function to railway tracks or freeways (Refer Fig. 7). Three different families of motor proteins have been identified: Kinesin and dyneins move along tubulin filaments, myosin move on actin filament. The filaments are periodic and fairly rigid structures with a period of the order of 10 nm.

The swimming nano-bio-organisms use active and rotating or beating cilia or rotating flagella [24, 25] as major methods of movement. These biologicals cannot rely on drifting by inertia, as macro-objects do when swimming; they immediately come to a halt when they stop their beating motion. They move by non-reciprocal periodic motion obtained by beating of flexible oars (cilia or flagella). The conformational change over a period is asymmetric for flexible oars and guarantees a net motion. They are used by small cells like mammalian spermatozoa to swim and internal organs to pump liquids.

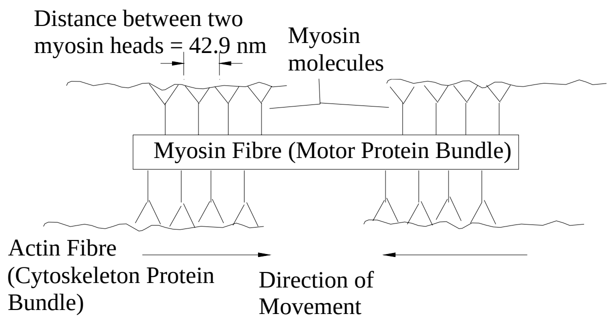

Fig. 7 Schematic of sliding movement of a myosin fiber on an actin filament

Flagella of bacteria are helical stiff polymers set in motion at their base by a rotary motor. This also yields non-reciprocal motion in a cycle; one cannot swim at low Reynolds number with stiff oars and symmetric conformal changes. Biologicals, therefore has approached the difficulty by having either flexible oars (cilia and flagella) or stiff helical shapes. Hydrodynamic friction converts the rotational motion of the helix into thrust along the helix axis (Refer Fig. 8)

Another challenging aspect of motion in nano-domains is that the Brownian storms rage relentlessly and refuge from the random Brownian motion in solutions is found by resting on surface. Indeed, nature uses the concept of the Brownian ratchet to excellent effects in the action of linear and rotary protein motors [79]. Although biological motors are capable of complex and intricate functions, a key disadvantage of their applications ex vivo arises in their inherent instability and restrictions in the environmental conditions [80]. In vivo, one can make nano-swimmers with asymmetric conformational changes by either using flexible oars or stiff helices but even then low fuel efficiency issues predominates and Low Peclect number in nano-domains makes the issue of movement more involved and interesting which is discussed next.

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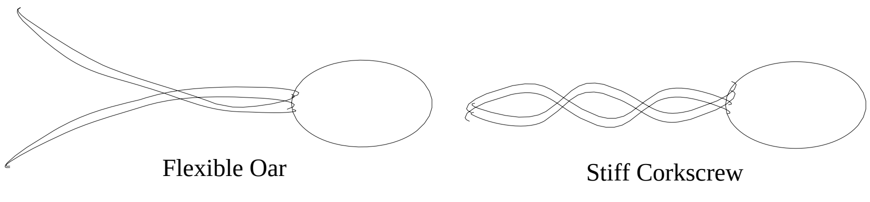

Fig. 8 Schematic of mechanisms in biologicals for obtaining non-reciprocal motion

5 Efficiency aspect of motion in nano-domains

The low inertia and high viscous forces are coupled with low efficiency and low convective motion in nano size regimes. For example, motion by beating of cilia and flagella at 30 μm/sec with 1% efficiency costs 2×10^{-8} erg/s in Bacterial movements [21]. The efficiency is too low when compared to ~30% in case of I.C. engines. Though the efficiency is poor but is only a small fraction of the metabolism and the energy budget of the Bacteria. The biological have sufficient amount of energy supply and are least concerned about energy efficiency. The issue of energy efficiency, though, will be of concern in nanorobots where power supply to the miniaturized robot and miniaturization of power supply both are going to be a challenge and nagging problem to engineers.

The dimensionless number called as Peclect number (*Pe*) given by lv/D is the ratio of time taken to cover a distance l at velocity v with a diffusion constant D [37]. The local stirring motion by beating of cilia and flagella will only work when Peclect number is greater than unity. In order to attain high values of *Pe* in nano- domains, velocity has to be increased almost 20 times. The efficiency will come down drastically even from 1% value of biologicals. The motion by diffusion may be more effective choice in comparison to convective motion. In order to achieve higher Peclect number at low Reynolds number, the diffusion of the nano-robot will play a vital role. Moreover in nano-domains, the non-rigid nature of the moving links of nanorobots is also to be taken into account. The author has proposed a non-rigid model of nanoparticle (sphere) performing Brownian motion in earlier work [17, 38, 39]. The model is shown in Fig. 9 and the analytical expression of the motion considering the synergism of local and global motion is given as Eq. (3) [40].

$$l = \sqrt{E\{x^2(t)\}} = \sqrt{\frac{\kappa T m}{f^3}\left\{\frac{\begin{array}{l}(f\,f' + mk)(f + f')\\ +(\omega\,m\,f' - f\,k/\omega)\\ \times(\omega\,m - k/\omega)\end{array}}{(f + f')^2 + (\omega\,m - k/\omega)^2}\right\}P\,Q} \qquad (3)$$

where $P = \left\{1 - e^{-f\,t/m}\right\}$ and $Q = \left\{\frac{2\,f\,t}{m} - 1 + e^{-f\,t/m}\right\}$.

The synergism of local and global deformations during motion has been extended to motion of nanoparticle considering viscoelastic medium [41] and 1-DOF nano-link [42]. The model is further verified to corroborate with Plank’s radiation model [43] justifying the basic hypotheses of local and global deformation.

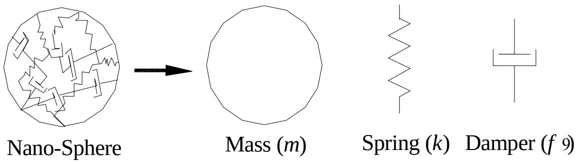

Fig. 9 Model of Non-rigid Nanoparticle (Sphere)

Equation (3) constitutes of four parameters representing inertia (m), coefficient of absorption of energy i.e. spring constant of nanoparticle (k), coefficient of dissipation of nanoparticle (f') and that of medium (f). The plausibility of engineering either of the parameter and not only inertia opens possibility for diffusion acceleration or deceleration. The future may see realization of nanorobots where design is done to enhance movements based on diffusion in addition to convection thereby increasing the efficiency.

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