Hybrid Synthetic/Bio Motor/Generator

NSF NSEC Grant EEC 0425914
PIs: **Alex Zettl, George Oster, Jean Frechet, Michael Crommie, Carlos Bustamante**
University of California at Berkeley

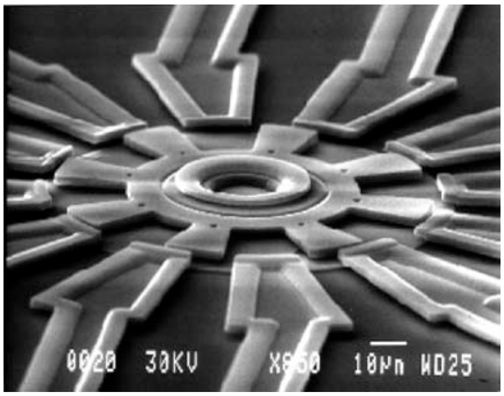

Fig 1. MEMS rotational motor [1].

The miniaturization of electronic devices has revolutionized the technology of today, but the miniaturization of mechanical devices promises to revolutionize the technology of the future. Recent progress in MEMS (micro-electro-mechanical systems) has already begun this revolution by miniaturizing a wide range of mechanical sensors/actuators and integrating them onto silicon chips. The size of state-of-the-art MEMS devices, however, still measures in the microns - significantly larger than the constituent atoms and molecules that make up matter. Yet, there is no fundamental reason why machines and motors cannot be scaled down to the nanometer size of individual molecules. Such nanoelectromechanical devices and systems (NEMS) would provide completely new methods for manipulating matter and for interfacing with biological systems.

Nature has many exquisite examples in nanomechanics. Organic molecular motors abound in biological systems and can perform tasks involving molecular motion and conversion of chemical to mechanical energy. Examples are actomyosin, RNA polymerase, and ATP synthase [2]. Such bio-motors are evolutionarily perfected molecular assemblies that undergo precise conformational changes under the influence of well-controlled chemical reactions. A drawback of biological motors, however, is that they are restricted to operate under a limited set of physiological conditions. Biological motors must thus be augmented with new varieties of “artificial” nano-machines in order to create a flexible nanomechanical technology that would operate at expanded bandwidth, temperature and in diverse environments.

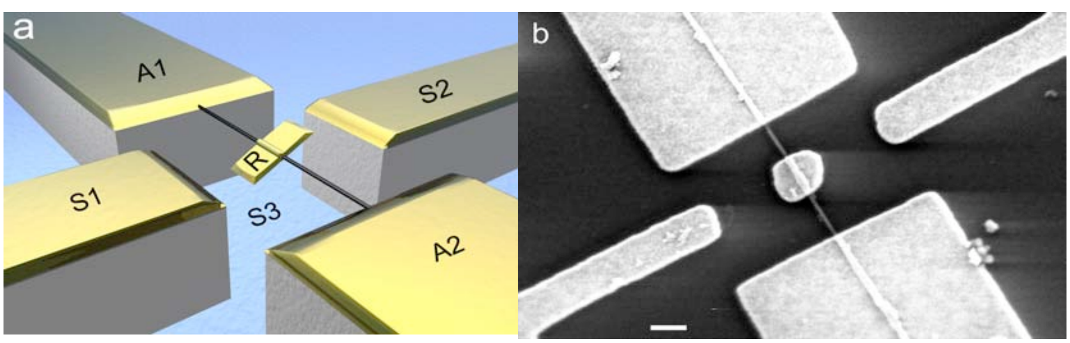

Fig 2. **(a)** Schematic motor layout. R: nanotube suspended metal plate rotor. A1, A2: anchors. S1, S2, S3: stators. **(b)** SEM image of completed nanomotor. Scale bar 300 nm.

Researchers at the Center of Integrated Nanomechanical Systems (COINS), based at the University of California in Berkeley, have been working to understand synthetic and biological nanomotors. The Zettl group has nanofabricated synthetic motors based on multiwall carbon nanotubes (MWCNTs)(Figure 2). MWCNTs are nested structures of concentric cylindrical graphene shells. Their atomically perfect structure should be ideal for creating nanoscale rotational bearings. Figure 3 shows a nanomotor in operation[3].

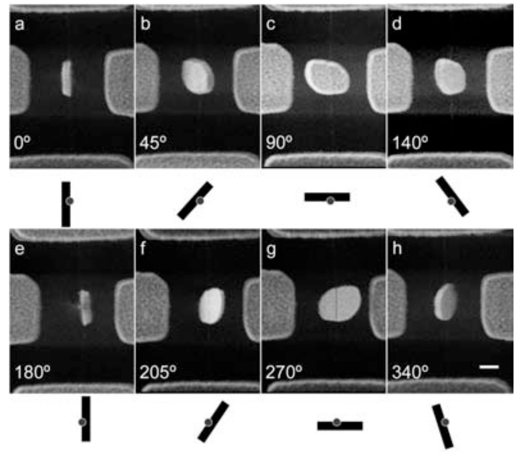

Fig 3. Micrographs of a nanomotor stepped through 360°. Scale bar 300 nm.

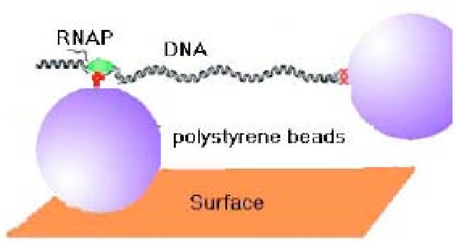

Fig 4. RNA polymerase molecular motor transcribes DNA tethered to a surface using polystyrene beads.

However, there are many important lessons to be learned from the design and operation of biological molecular motors. For example, estimates of the energy efficiency reveal that many of these molecular motors operate with astonishingly high efficiencies, in several cases approaching 90% or higher. How are these enormous energy conversion efficiencies attained? Because of their molecular dimensions, many frictional and other dissipative processes are undoubtedly minimized during the operational cycle of the motor. The methods of single molecule manipulation developed in the Bustamante group[4] are being used to investigate, one molecule at a time, the physical principles that govern the behavior of molecular motors. In the first phase of these endeavors, translational and rotational biological motors will be attached to nano-fabricated moving parts in order to drive them (Figure 4). Theoretical guidance is provided by the Oster group, which studies the biomechanics of molecular motors from the viewpoint of mesoscopic modeling[5]. These nanometer-sized, biochemically fueled devices will constitute a step towards combining biological motors with artificial electrical and mechanical motors, and finally to a hybrid integrated system (Figure 5).

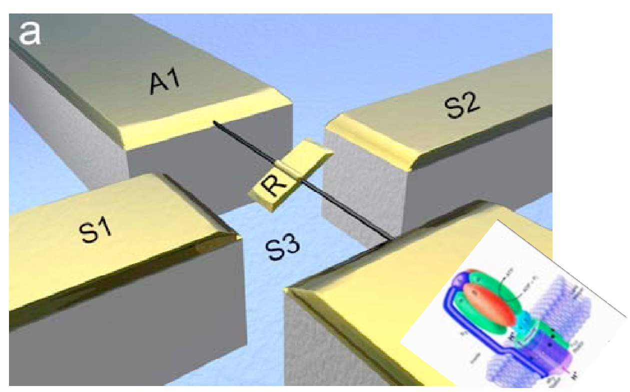

Fig 5. Schematic showing a chemical motor attached to a nanotube-based synthetic motor.

References

For further information about this project link to http://nano.berkeley.edu/coins/.

[1] L. S. Fan, Y.C. Tai, R.S. Muller, *Sensors and Actuators* **20**, 41 (1989).
[2] S.J. Hong, P.L. Petersen, ATP synthases: Insights into their motor functions from sequence and structural analyses, *J. BioEng. Biomembr*. **35**, 95-120 (2003).
[3] A. M. Fennimore, T. D. Yuzvinsky, W. Han, M. S. Fuhrer, J. Cummings, A. Zettl, Rotational actuators based on carbon nanotubes, *Nature* **424**, 408, 2003.
[4] Smith DE, Tans SJ, Smith SB, Grimes S, Anderson DL, Bustamante C. The bacteriophage straight phi29 portal motor can package DNA against a large internal force. *Nature* **413**:748-52 (2001).
[5] Sun, S., Wang, H., and Oster, G. Asymmetry in the F1-ATPase and its implications for the rotational cycle. *Biophys J*. (2004).