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# Temperature effects on disk-like gold-nickel-platinum nanoswimmer's propulsion fuelled by hydrogen peroxide

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ABSTRACT

Self-propelled nanoswimmers are designed in a disk shape, consisting of tri-metallic segments: gold (Au), nickel (Ni), and platinum (Pt). A bubble propulsion mechanism originated from momentum change of a Au-Ni-Pt nanoswimmer-oxygen ($O_2$) bubble integral system is proposed. This innovative type of Au-Ni-Pt segmented nanoswimmers is fabricated using a layer-by-layer deposition method based on nano-electro-mechanical systems (NEMS) technology, whereby Pt functions as the chemical catalyst for the decomposition of hydrogen peroxide ($H_2O_2$) to produce $O_2$ bubbles detaching from its surface and water ($H_2O$), which in turn generates a recoil force to thrust the nanoswimmers propelling forward. Two different sized nanoswimmers' motion is characterized by changing the temperature of $H_2O_2$ solution, revealing that $O_2$ bubbles are generated and detached from the surface of Pt, and the nanoswimmers can autonomously propel forward in either a linear or a circular way. Results show the big nanoswimmer propels forward faster than the small one at temperature below 27 °C, while the small nanoswimmer moves forward faster at temperature above 27 °C. In general, the speed of nanoswimmers is increased with the increment of the temperature of $H_2O_2$ solution, thus the propulsion of the nanoswimmers is temperature-dependent.



## 1. Introduction

A nanomotor is a nanoscale device, which has the capability to convert energy into mechanical movement or force [1]. In nature, living systems possess their intelligent and efficient bio-molecular motor proteins for various functions through millions of years of evolution [2]. Microorganisms can drive themselves in aqueous media with the aid of mechanical conformational deformation of their own solid appendages using the energy they harvest from the surrounding environments [3]. For instance, bacteria are able to propel forward using the rotational flagellar nanomotors, which are powerful molecular nanomotors, transforming ion motive force (IMF) into rotary kinematic motion [4]. Moreover, linear bio-molecular nanomotors, such as kinesin, myosin and dynein, are capable of coupling hydrolysis of adenosine triphosphate (ATP) into adenosine diphosphate (ADP) and phosphate (Pi) for lateral movement along the corresponding tracts (actin or microtubule filaments), in order to transport numerous functional cargoes *in vivo* [5,6]. In addition, biological cells are equipped with molecular engines, which are desired to generate the biological fuel ATP. These engines are the rotary molecular nanomotors of F- and A-ATP synthases. Both of them consist of two distinct reversible rotary motors which can operate in different types of fuel. One is a soluble motor ($F_1$ or $A_1$ motor), which synthesizes ATP molecules. The other one is a hydrophobic transmembrane motor ($F_o$ or $A_o$ motor), which is powered by a concentration gradient of biochemical ions ($H^+$, $Na^+$) as well as functions like a turbine [7,8].

Evolution bestows bio-molecular motor proteins with fascinating abilities to harvest energy from surrounding environments for the autonomous movement *in vivo* described above [2–8]. Inspired by naturally occurring bio-molecular nanomotors, researchers extensively paid great efforts on artificial nanodevices. They tried to model, simulate, design and fabricate devices, which were able to mimic the autonomous propulsion of bio-molecular nanomotors

*Abbreviations:* Au, gold; Ni, nickel; Pt, platinum; NEMS, nano-electro-mechanical systems; $H_2O_2$, hydrogen peroxide; $O_2$, oxygen; $H_2O$, water; IMF, ion motive force; ATP, adenosine triphosphate; ADP, adenosine diphosphate; Pi, phosphate molecule; $H^+$, proton; $Na^+$, sodium ion; PDMS, polydimethylsiloxane; DI, deionized; Si, silicon; $H_2SO_4$, sulfuric acid; $SiO_2$, silicon dioxide; PECVD, plasma enhanced chemical vapor deposition; HMDS, hexamethyldisilazane; rpm, revolutions per minute; RIE, reactive ion etch; UV, ultraviolet; KOH, potassium hydroxide; SEM, scanning electron microscopy; EDS, energy dispersive spectrometry; MAE, Mechanical and Aerospace Engineering; NTU, Nanyang Technological University.

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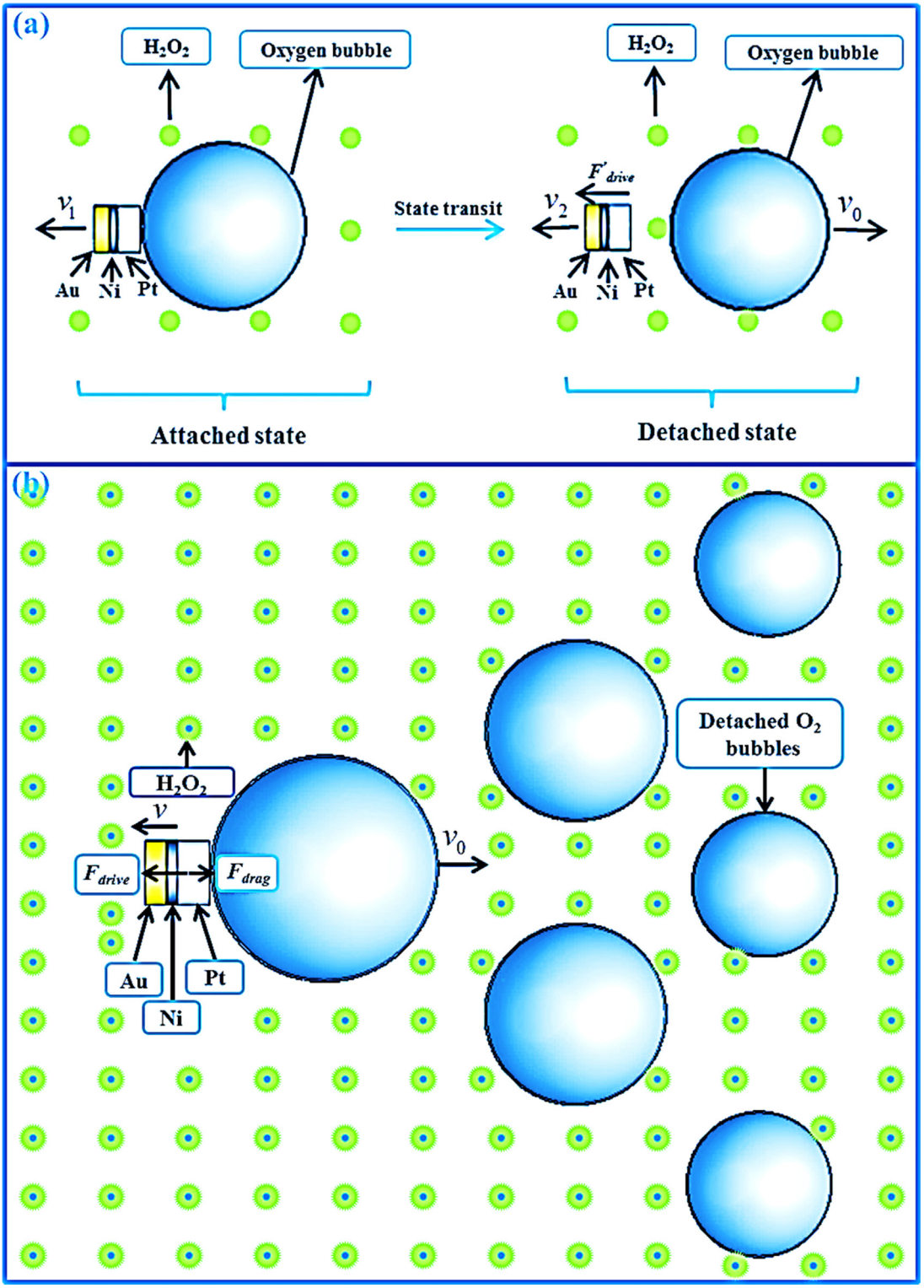


**Fig. 1.** Schematic diagram of the propulsion of the disk-like Au-Ni-Pt segmented nanoswimmers. (a) Demonstration of a recoil force $F'_{drive}$ originating from momentum change induced by the detachment of one single $O_2$ bubble. $v_1$, $v_2$ and $v_o$ denote the joint velocity of the nanoswimmer and $O_2$ bubble before the detachment of the $O_2$ bubble, velocity of the nanoswimmer after the detachment of the $O_2$ bubble and original velocity of the detached $O_2$ bubble, respectively. (b) Representation of the propulsion of the Au-Ni-Pt nanoswimmers in aqueous $H_2O_2$ solution. At steady state, the values of $F_{drive}$ and $F_{drag}$ are equal, thus the nanoswimmers reach a constant velocity of $v$.

existing in living bodies. For example, Ismagilov and his colleagues firstly developed a millimeter-scale object driven by the detachment of $O_2$ bubbles in 2002 [9]. This motion system consisted of a thin polydimethylsiloxane (PDMS) plate, which was firstly mounted with a piece of Pt-coated porous glass filter by a stainless steel pin. Afterwards, the assembled system was immersed into aqueous $H_2O_2$ solution. Pt catalyzed the decomposition of $H_2O_2$ to create $O_2$ bubbles detaching from its surface, which in turn generated a driving force to propel the motion of the system. Since then, researchers devoted their interests into this research field.