Review

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Recent advances of light-driven micro/nanomotors: toward powerful thrust and precise control

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Abstract: In the past two decades, micro/nanomotor is emerging as a critical domain of nanoscale research. Light-driven micro/nanomotors have gained a wealth of attention from the academics because of their potential applications in various fields such as environment remediation, biomedical field and cargo delivery at microscale. In order to perform some more challenging and complex tasks, higher actuation force and more precise control are both indispensable for light-driven micro/nanomotors. In this review, we discussed about three major factors: actuation mechanism, structure of micro/nanomotors and the wavelength of light irradiation, to find out how to gain a higher actuation force and propel the motor in a relatively high speed under light irradiation. Besides, some common control strategies of light-driven micro/nanomotors are presented in details with the advantages and disadvantages of each control mechanism, which will help lead to a convenient and precise control. Finally, the future development approaches toward powerful thrust and precise control are discussed for light-driven micro/nanomotors.

Keywords: actuation force; light driven; locomotion control; micro/nanomotor.

1 Introduction

Micro/nanomotors are exquisite devices designed at micro/nanoscale, which can actuate themselves with various types of energy to realize the desired functions, playing an important role in biomedical, environmental and micro/nano engineering fields [1–4].

The development of micro/nanomotors has gained tremendous attention from the academics all over the world. The past two decades have witnessed great success of the micro/nanomotors. Beginning in 1959, Richard P. Feynman, a famous physical scientist, came up with the idea of “manipulating and controlling matter at a small scale” in his influential talk “There’s plenty of room at the bottom” [5], in which he proposed pioneering conjecture kinds of possibilities and challenges in the future nanoworld such as manipulating individual atoms and fabricating extremely tiny devices [6]. With the movie “fantastic voyage” released in 1965, more and more researchers turned to be interested in how to construct an exquisite nanoworld using micro/nanomotors. During recent years, there were numerous micro/nanomotors based on different types of actuation approaches proposed and fabricated to conduct complex tasks [7–9].

From the perspective of actuation energy source, the reported work on micro/nanomotors can be categorized into five classes. In general, the actuation energy source of micro/nanomotors includes chemical fuel [10–14], magnetic field [15–19], electric field [20–23], ultrasonication [24–27] and light field. Chemical fuel often provides power to generate bubbles or chemical gradients to thrust the propulsion of micro/nanomotors, such as active metal’s reaction with water and decomposition of hydrogen peroxide. Micro/nanomotors based on chemical fuels can easily reach a high speed and move relatively fast in viscous cell culture medium. However, the chemical fuel powered motors are suffering from uncontrollability of the motion and toxicity of the chemical fuels used. Ultrasonication is a novel actuation energy source employed for micro/nanomotors in recent years. The motors are
propelled by tuning the ultrasonication field distribution. Ultrasonication provides a relatively strong propulsion force for motors, but higher requirements on the equipment are necessary. The motion of micro/nanomotors with component of magnetic materials can be easily controlled under a changed magnetic field. Both the moving direction and velocity will be adjusted as the current in coils changes; thus, the main problem is to build a controllable magnetic field in consideration of limited applied area, structure of three-dimensional magnetic coils and so on. Electric field drives the micro/nanomotors by the electric field gradient, through which motors can move to low potential positions. Thus far, the motion of most electric-field-driven micro/nanomotors is limited within a two-dimensional surface, although research on three-dimensional motion control of motors using electric field is starting to soar.

Light, especially sunlight, is the major energy source that powers our world and lives. With the outstanding merits including abundance, remote propagation, clean energy input and nice controllability, light has been acknowledged as a promising energy source for driving micro/nanomotors. First reported in the 1980s [28], light-driven micro/nanomotors have become more and more well-known during recent years [29–32]. Various kinds of light-driven motors have been proposed and developed; not only the structure but also the actuation mechanism can differ from each other. Herein, following a brief introduction about the background information of light-driven micro/nanomotors, some potential applications of micro/nanomotors, which are promising with applications ranging from environment, biomedicine to nanoeengineering fields, will be presented next. Subsequently, in order to gain higher actuation force to propel the motor at a high speed, we discussed about three main factors: actuation mechanics (including photothermal propulsion, bubble propulsion, self-electrophoretic propulsion and osmotic propulsion), structures (including microsphere, nanorod, nanotubular and asymmetric branches) and the light wavelength (including near infrared (NIR), visible (Vis) and ultraviolet (UV) lights), each of which has a significant influence on the driving force for light-driven micro/nanomotors. As for the motion control, we introduced several mostly used strategies such as the “on/off” switch, intensity of the light irradiation and magnetic field. Despite the excellent prospects of micro/nanomotors, there are still some challenges waiting for better solutions. Some recent reviews have covered the internal mechanisms or application prospects of micro/nanomotors in detail. For example, Xu discussed some fundamentals and applications of light-driven micro/nanomotors mainly [30], M. Safdar focused on the environment remediation in his review [33] and Wang’s [31] topic was toward photochromism in nanosystems. In this review, after an introduction about applications of micro/nanomotors, we found that some existing motors cannot meet the demand of all kinds of environment and that there are still some factors waiting for further improvement, such as the driving force and controlling method. Thus, we discussed different actuation mechanisms, structures and light irradiation wavelength of micro/nanomotors and collected data from papers published in recent years to compare the driving force and velocity of the different kinds of motors. It was concluded that bubble propulsion, microsphere structure and UV light irradiation can lead to a high actuation force. After which, in order to gain more precise control, we listed some common controlling strategies in detail and discussed the advantages and disadvantages over each other. We hope that this review can provide a more comprehensive summary about recent light-driven micro/nanomotor studies to guide the further promotion of driving force and locomotion control for the motors.

2 Potential applications of light-driven micro/nanomotors

Because of special advantages of light-driven micro/nanomotors such as microscale, easy to control by light intensity and fast response to light irradiation, they can play an influential role in some unique applications involving environment remediation, biomedical field and cargo delivery at microscale.

2.1 Environment remediation

Because of the rapid development of global industrialization since the Industrial Revolution, more and more polluted water has been released into lakes, rivers and seas. Compared with conventional solutions to the water pollution such as putting detergents or placing filtration membrane in polluted areas, micro/nanomotors especially the light-driven micro/nanomotors can reach a higher efficiency while consuming much less energy to remove biological and chemical pollutants, especially at some areas where common methods cannot reach. Once such motors are put into polluted water, they can be driven under sunlight and move randomly, which can ensure a large coverage in water [34–37].
For example, Qu et al. described a kind of micromotor with an enhanced photocatalytic effect, which facilitate the degradation of rhodamine B and methyl orange, just as depicted in Figure 1A. Also, as illustrated in Figure 1B, such light-driven TiO$_2$/Au micromotors can move in water freely under UV light irradiation. With the number of motors increased, the ability of decontamination was promoted [37]. Using Au-WO$_3$@C Janus micromotors, dye pollutants were removed under UV light as well [43].

### 2.2 Biomedical application

In the biomedical field, micro/nanomotor with the advantage of tiny size has been adopted into drug delivery and cell inactivation. Because of their fast motion, directional control and tissue penetration ability, self-propelling micro/nanomotors hold exciting prospects to carry drug therapeutics to the target. Besides, motors with photothermal effect can generate a high temperature surrounding under NIR light irradiation, which can kill some diseased cells and tissues [44–51].

NIR-light-driven micro/nanomotors are of special interest for applications in the biomedical field because of the highest transmissivity of NIR light through body tissues. The reported NIR-light-driven motors are usually based on the photothermal effect (as depicted in Figure 1C), which can absorb the incident light and induce a temperature gradient around the motors to propel their motion [39]. In Figure 1D, cancer cells were selectively killed with nanomotor based on Pt nanoparticles through photothermal ablation effect [40]. Light-driven micro/nanomotors were also adopted to direct the growth of nerve cells, as shown in Figure 1C [52].

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**Figure 1:** Applications of light-driven micro/nanomotors in environment remediation, biomedical field and cargo delivery. (A) Micromotors with plasmonic photocatalyst are fabricated to degrade organic pollutants rhodamine B and methyl orange [38]. Copyright 2016, The Royal Society of Chemistry. (B) Light-driven TiO$_2$/Au micromotors and enhanced motion in dye samples. The percent decontamination of methylene blue (MB), cresol red (CR) and methyl orange (MO) with an increased number of motors are shown [37]. Copyright 2017, Springer. (C) A bovine serum albumin/poly-l-lysine (PLL/BSA) micromotor, which is fabricated with biodegradable protein, was successfully applied into cancer drug encapsulation, delivery and release, which is controlled by NIR light [39]. Copyright 2014, American Chemical Society. (D) A NIR-light-triggered polymeric stomatocyte nanomotor developed for cancer cell killing through photothermal ablation effect [40]. Copyright 2017, American Chemical Society. (E) Schematic of light-driven material delivery using liquid marbles, which serve as micromotors [41]. Copyright 2016, Wiley-VCH. (F) Self-propelled micromotor that can be steered to a tiny cargo many times than its size and transport the cargo to a remote location as well as release it [42]. Copyright 2013, American Chemical Society.
2.3 Cargo delivery at microscale

Just akin to the real factory, there are many “cargos” at micro/nanoscale that need to be loaded and delivered, which can be potentially applied into micro/nano-engineering and the component of micro/nano-assembly. It is an essential section if human beings are intent to develop micro-manufacturing. Therefore, the micro/nanomotors, which can be easily and precisely controlled, are in demand to execute complex tasks [41, 53, 54].

Light-driven liquid marbles, which worked as micro-motor, were reported to deliver and release materials in a controllable way (Figure 1E) [41]. As shown in Figure 1F, cargos at microscale were transported to the desired destinations along the designed trajectories using a light-driven TiO₂ micromotor.

As we can see, in spite of the wide ranges of applications and convenience of light-driven micro/nanomotors, it is not easy to meet all the demands. Motors with high driving force and precise control are getting more and more concentration. For example, for environment remediation, such light-driven micro/nanomotors are required to move automatically to those seriously polluted areas at a high speed; thence, it is essential to ensure actuation force to be high enough to propel the motor. Conversely, precise control is also in demand to help motors follow the designed route. Furthermore, enhancing the actuation force and promoting the locomotion control accuracy simultaneously is a prerequisite in broadening the application fields of light-driven micro/nanomotors.

3 Actuation force of micro/nanomotors

Because of the tiny size of micro/nanomotors, their Reynolds numbers in liquid are so small that the inertial force is negligible. To overcome the drag force while moving in viscous fluid such as cell culture medium, it is necessary to produce sustainable and powerful actuation force to help the motion of micro/nanomotors. In the past two decades, scientists have devoted to find an effective, convenient strategy to propel the micro/nanomotors, and with the outstanding merits of clean, sustainable and easy to control motion speed, light has been revealed to be a fantastic choice to achieve this goal. Aiming at higher actuation force, the actuation mechanisms, structures and wavelength of light irradiation are discussed in this chapter.

The category of driving force is decided by different actuation mechanisms, as seen in Figure 2. In photothermal-effect propulsion, the thermophoresis force generated from the temperature gradient propels the motor along...
with the temperature decline. For self-electrophoretic propulsion, self-generated electric field will help charged micro/nanomotors move ahead with the electrophoretic force. Then, in bubble-induced propulsion, thrust force from bubbles will push the motor to move in an opposite direction. Lastly, in osmotic propulsion, some “substances” can be generated under light irradiation, but this kind of substance is neutral, which can form a zone with high product concentration. The diffusiophoretic force will propel the motor to the side with lower concentration. As for the different kinds of structures, some structures are suitable for specific mechanisms; for example, bubble propulsion often makes use of the hollow structure of nanotubular. We will discuss it in detail in this chapter. Besides, the wavelength of light irradiation has a great influence on the actuation force, because there are different kinds of material response to various lights, which have varied photon energy; thus, their actuation effects are expected to have an obvious difference.

3.1 Actuation mechanisms for micro/nanomotors

Until now, some actuation mechanisms, such as photothermal-effect propulsion [39, 55–60], bubble-induced propulsion [45, 61–68], self-electrophoretic propulsion [42, 69–77] and osmotic propulsion [43, 78–81], have been successfully achieved and promote the development of light-driven micro/nanomotors dramatically.

3.1.1 Photothermal effect propulsion

Upon NIR irradiation on the face of micro/nanomotors, the electromagnetic energy absorbed is dissipated as heat and then forms a thermal gradient around the surrounding liquid [82]. This increased temperature gradient results in the motion of the self-thermophoresis of photothermal materials, and therefore, the motion of motors can be controlled by the NIR laser illumination intensity. Higher light intensity leads to a higher temperature gradient and subsequently results in a higher actuation force of the micro/nanomotors. The thermophoretic force can be described as follows [59]:

$$F = \frac{9\pi d_p \eta k_p}{2\rho r} \Delta T(r,t)$$

where $d_p$ is the particle diameter, $\eta$ is the viscosity of fluid, $k_p$ is the thermal conductivity of fluid, $r$ is the fluid density and $t$ is time. It can be found that the thermophoretic force is concerned with the real-time temperature gradient, the particle diameter and the fluid mechanical properties.

Early in 2014, Wu and Lin have found an approach to modulating the on-demand motion of catalytic polymer-based microengines via NIR laser irradiation [55]. As obtained through the calculation according to the heat diffusion equation, the temperature shows a gradient distribution around the micromotor. While the half-metal coated colloidal particles were under NIR light irradiation, the metal side would transform the light energy to heat and lead to a sharp decline of temperature distribution at the surface of motor. The motion speed of the NIR light that actuated the Janus motor can reach up to 10 $\mu$m/s (as shown in Figure 3A). Just several years later, some researches figured out that the microsphere structure based on NIR irradiation can have a higher driving force, the maximum velocity of which goes up to 950 bodylength/s [60], far higher than the other motors. As shown in Figure 3B and C, the microsphere is half coated with Au, converting the absorbed energy to heat, and therefore, the hot Au nanoshells act as a heating source and generate local thermal gradients across the micromotors. Closer to the center, the temperature gets higher and declines more rapidly, and then the motor moves toward the opposite direction of the declining temperature at a speed as high as 42 $\mu$m/s.

In summary, the photothermal-effect propulsion mechanism for micro/nanomotors makes use of the temperature gradient under the laser irradiation to stimulate the motion of motors in liquid surroundings. Advantages of this actuation mechanism include the ease in moving in a high speed under a strong laser irradiation, as the reaction is vigorous. However, this kind of motors may be fatal to biological samples because of the local high temperature and the direction of motion cannot be controlled very precisely as the control of the temperature field distribution is a great challenge.

3.1.2 Bubble-induced propulsion

Bubble propulsion, as the name suggests, propels the motor by generating bubbles through chemical reactions [83, 84]. As bubbles are released from the surface of motors, it results in a driving force away from the surface of motors. The driving force is assumed to be balanced with the viscous drag force if the vertical forces are ignored, and the viscous drag force can be evaluated by employing the following equation [85]:
where $\mu$ is the liquid dynamic viscosity, $r$ means the equivalent radius of the micro/nanomotors and $V$ represents the stable motion speed of micro/nanomotors. Thus, the motion of micro/nanomotors based on the bubble propulsion is directed away from the side of the bubble generator.

In early studies, Oliver G. Schmidt and his colleagues engineered a rolled-up microtube with an inner catalytic surface, serving both as the chemical reaction chamber and as the gas-collecting cavity, from which the bubbles were then released that propelled the microtubular to move in an opposite direction \cite{86}. In order to gain a higher driving force and velocity, it is necessary to increase the concentration of the chemicals involved in the reaction. However, it is well known that with the increased concentration of chemicals, the toxicity is expected to be higher. Another issue bothering the bubble propulsion mechanism is that the motion is very difficult to control because of the random bubble release.

Li and Mou et al. put up a new kind of light-controlled bubble propulsion of amorphous TiO$_2$/Au Janus micromotor, in which the UV light energy was transformed into chemical energy and subsequently into mechanical energy for micromotor fast motion in water \cite{64}. The power conversion efficiency ($\eta_c$) of such light-driven micromotor is defined as follows \cite{87}:

$$\eta_c = \frac{P_{\text{mecha}}}{P_{\text{light}} + P_{\text{chem}}} = \frac{6\pi \mu r V}{I \pi r^2 + N \Delta G^o}$$

Figure 3: Micro/nanomotors with photothermal-effect propulsion. (A) Theoretical photos of the photothermal effect and the motion speed with respect to the NIR laser power of Au-silica Janus particles \cite{82}. Copyright 2010, American Physical Society. (B) The measured temperature changes with respect to time and the calculated temperature distribution of a type of Janus mesoporous silica nanoparticle motor \cite{60}. Copyright 2016, American Chemical Society. (C) Simulated temperature profile, working mechanism schematic and motion behavior characterization result of photothermal effect propelled Janus micromotor under NIR irradiation \cite{58}. Copyright 2016, Springer.
H₂O₂ can be much lowered to generate O₂ bubbles. According to the calculation, the power conversion efficiency is about 10 times higher than that of the catalytic bubble propelled micromotors based on pure H₂O₂ decomposition on Pt [87]. Besides, the state and speed of motion can be reversibly, remotely and wirelessly controlled by regulating the “on/off” switch and the intensity of light irradiation. In Figure 4, in H₂O₂ solution, Pt [88] and amorphous TiO₂ [64, 65] produce peroxide complexes on the surface of the microstructures under white light or UV illumination. The separated electrons are transferred to the peroxide complexes, which leave behind the accumulated holes. This effect enhances the transportation of the electrons and holes in the decomposition of H₂O₂ to generate oxygen bubbles and speed up the reaction significantly.

Bubble propulsion can produce a high driving force, and the velocity is found to be higher than photothermal-effect propulsion. However, there are still some questions that need to be taken into consideration, such as the environment-unfriendly fuels, lack of precise motion direction control and undesired bubble generation.

3.1.3 Self-electrophoretic propulsion

Some chemical reactions induced by light irradiation rely on the properties of specific materials such as metals and semiconductors. In order to modify the chemical bonds by light, its energy content has to account for the bond energy [89, 90]. Micro/nanomotors designed with a bulk-heterojunction structure will generate ions through photocatalytic reactions in some salt solutions with incident light. Self-electrophoresis refers to the actuation of charged micro/nanomotors through local electric field around them. The local electric field is the resultant of asymmetric distribution of charged ions, which are generated from the photocatalytic reactions on the surface of the micro/nanomotors, to be specific, on the surface of the different kinds of materials. As the electric field is generated under light irradiation, the charged micro/nanomotors are driven to move in response to the field [91, 92].

There has been some representative work on self-electrophoretic propelled micro/nanomotors reported in the past decade. Figure 5A displays the schematic diagram of a nanomotor with the form of a core-shell silicon nanowire, i.e. the inside p-type Si covered with a thin layer of n⁺–Si. Under NIR or visible irradiation, the core-shell silicon nanomotor works as a solar cell, generates photovoltage along the nanomotor in H₂O₂ or Q/QH₂ solution and then forms an asymmetric distributed positive and negative charges on the p-type and n-type parts, respectively [93]. Another Janus motor made by TiO₂ and SiO₂ is illustrated in Figure 5B. e⁻ is transferred from the valence band to the conduction band inside the motor, the generated electron-hole pairs will help the photocatalytic decomposition of H₂O₂ on the surface of motor, and the concentration of H⁺ differs with each other on the TiO₂ side and SiO₂ side, leading to the self-electrophoretic propulsion toward the TiO₂ side under UV light irradiation [73]. In Figure 5C, at the end of Si, oxidation reaction
occurs between Si and SiO₂, resulting in the generation of protons. Thus, the resulting proton gradient forms an electric field, which provides a driving force on particles [75]. While in Figure 5D, the electron-hole pairs are generated in the iron oxide and separated at the iron oxide/solution interface when the motor is under Vis light irradiation. Electrons are transferred from the n-type iron oxide to the gold side, and holes are driven to the iron oxide side through band bending. Therefore, the decomposition of H₂O₂ will be catalyzed at the gold and iron oxide sides, respectively, leading to a proton concentration gradient around the opposite side of the motor [76].

To sum up, this kind of micro/nanomotors can be activated by UV or Vis light at a very low concentration of chemical fuel, the speed of which can be modulated by the light intensity easily, and the whole process is smoother than the other driving mechanisms introduced above. However, the driving force cannot reach to a high value, so the velocity is lower compared with the other mechanisms.

### 3.1.4 Osmotic propulsion

Just like the self-electrophoretic propulsion mentioned above, osmotic propulsion can also generate some “substances” through the chemical reaction under light irradiation, but this kind of substance is neutral, which can form a zone with high product concentration. Therefore, fluid flows from one side to another, resulting in the self-diffusiophoresis of motors [42, 94].

According to the study by C. Chen, the motion velocity \( U \) of the micro/nanomotors driven by the osmotic propulsion can be described as follows [78]:

\[
U = \frac{kT}{\eta} KLVC
\]

in which \( k \) is the Boltzmann constant, \( T \) represents the solution temperature, \( \eta \) is the viscosity of the liquid, \( K \) represents the Gibbs absorption strength, \( L \) is the motor length and \( VC \) is the molecule concentration gradient. In common, the diffusivity of the neutral substance is very slow because the magnitude of \( VC \) is much lower than the other gradient, so the velocity cannot reach much higher.

Taking the WO₃/Au Janus micromotor as an example in Figure 6A [43], UV light irradiation can activate photochemical reactions around the micromotor and lead to the formation of different species, such as \( \cdot \text{OH} \) and \( \text{O}_2^- \), and a molecule concentration gradient. As a consequence, the micromotor can be propelled based on the self-osmotic mechanism. \( \text{O}_2 \) molecules can be generated through the
decomposition of $\text{H}_2\text{O}_2$ around TiO$_2$ micromotors [95] and dissolve into water. The $\text{O}_2$ concentration gradient will actuate the micromotor movement (Figure 6B) [78]. The self-assembly effect of platinum nanoparticle decorated graphite-like carbon nitride nanomotors was revealed to be the result of osmosis under light irradiation, as illustrated in Figure 6C [96], and in Figure 6D, by catalytically decomposing $\text{N}_2\text{H}_4$ gas molecules are generated near the Ir/SiO$_2$ micromotor and form a concentration gradient, which drives the motion of micromotor through osmosis effect [79].

Comparing with the other three kinds of actuation mechanisms for light-driven micro/nanomotors, osmotic propulsion can be controlled more easily under light irradiation because of the stable osmotic gradient and is friendlier to the environment. However, its notable weakness is that the actuation force of this type of motor is smaller than the others, leading to a considerably humble velocity.

### 3.2 Different geometric structures for micro/nanomotors

The structure of micro/nanomotors has a significant impact on its motion; a different structure has its own characteristic to adapt to the environment or complete some complex tasks more conveniently. Through a summary of the reported work on light-driven micro/nanomotors, we find that there are four major kinds of structures, including microsphere, nanorod, tubular and asymmetric branches, designed to meet these demands [96–102]. Some detailed information and a comparison of the different structures will be presented below.
3.2.1 Microsphere structures

Microspheres are small spherical microparticles, with diameters typically ranging from 0.1 to 100 μm. With the streamlined structure, microspheres can reduce the viscous resistance effectively while moving in the fluid. The driving force can be balanced by the drag force approximately calculated in Equation (2) [85].

Microspheres can be applied into all kinds of situations including those four actuation mechanisms introduced above because of their wide applicability and are always made of some metal or metal oxide materials. For example, in Figure 7A, by depositing Pt thin film on Au microspheres, a type of conductive Au/Pt Janus nanomotors is synthesized [103]. Such bimetallic Au/Pt micromotors can move fast in H₂O₂ solution and repair cracks on conductive thin film autonomously. Both gold and platinum are relatively expensive as they are notable metals.

Besides, some cheap semiconductors materials, such as SiO₂ and TiO₂, have been employed to fabricate the microspheres as well. Figure 7B presents a scanning electron microscopy (SEM) image of TiO₂ microsphere half coated with Au as well as its energy-dispersive X-ray spectroscopy images for Ti, O, Au. Because of the self-electrophoresis actuation mechanism, the motion speed of the TiO₂/Au micromotor is dependent on not only the light intensity but also the thickness of Au [71], and as displayed in Figure 7C, the Au/WO₃@C micromotors, shaped in microsphere, have an average diameter of 1 μm. As aforementioned, the as-prepared WO₃@C microspheres have the WO₃ nanoparticles, clearly indicated from SEM characterization, decorated on the surface of carbon microspheres through solution process [43].

Figure 7: Structure of the microspheres employed in light-driven micro/nanomotors. (A) Schematic of the microsphere Au/Pt micromotor [103]. Copyright 2015, American Chemical Society. (B) SEM image and energy dispersive X-ray images for Ti, Au and O elements for the Au/TiO₂ Janus micromotor. The scale bar is 0.5 μm [71]. Copyright 2015, American Chemical Society. (C) SEM characterization results for Au/WO₃@C microsphere motors, whose average diameter is evaluated to be about 1 μm [43]. Copyright 2017, American Chemical Society.
to have a better performance than other structures. The maximum speed of microspheres reaches up to 50 bodylength/s, much faster than the other structures because of the simple and easy-activated model. However, as demonstrated in Figure 7C, the fabricated micro/nanosphere structure is also faced with the issue of weak uniformity, which is critical for large-scale application of micro/nanomotors.

### 3.2.2 Nanorod structures

Nanorods are often synthesized from metals or semiconducting materials and have an aspect ratio (length divided by width) of 3–5 [104]. A combination of ligands acts as shape control agents and bond to different facets of the nanorod with different strengths, and this allows different faces of the nanorod to grow at different rates, producing an elongated object [105]. In most reported work, nanorods are synthesized with templates, which include anodic alumina [76] and some organometallic polymer materials [75].

The motion of nanorods usually makes use of the self-electrophoretic propulsion. As the two opposite sides of the nanorod are made of different photolytic materials, oxidation reaction and reduction reaction occur separately, and charges travel from one side to another, causing a self-generated electric field to propel the micro/nanomotors. For example, Figure 8A presents both the SEM and transmission electron microscopy images of gold nanorods [57]. Under UV-Vis irradiation, the light-driven photo-electrochemical reaction generates anions and cations at opposite ends of the nanorod, resulting in an asymmetric distribution of the generated ions, which propels the nanorod by self-electrophoresis. To control the motion of nanorods better, Wang and his group have investigated the dependence of motion on the nanorod structure and revealed that the motion behavior changes with the end morphology of the nanorod (Figures 8B and 11B) [93]. Figure 8C shows the SEM image of a heterogeneous Au/Fe$_2$O$_3$ nanorod micromotor, whose motion speed and direction can be tuned by light intensity and external magnetic field, respectively [76].

### 3.2.3 Nanotubular structures

Different from the nanorod, nanotubular structures mostly utilize bubble-induced propulsion to promote the motion by taking advantage of the hollow structure [106]. Chemical reactions occur on the inner surface of the tubular and thus generate gas bubbles, which would be released from the tubular after growing into larger bubbles. Therefore, the size of both the ends is often designed a little different, helping bubbles to be released from the wider side. The recoil force during continuous expulsion of bubbles will propel the tubular to move at a high speed far away from the end bubbles releasing.

A type of Pt/ZnO micromotor with nanotubular structure is presented in Figure 9A [107]. As shown in Figure 9B, TiO$_2$ acts as the catalyst to help the decomposition of H$_2$O$_2$
to generate gas bubbles [64]. Because of the different width inside the tubular, bubbles will grow larger and be released from the wider side, which ensures the moving direction of nanotubulars. Figure 9C displays another type of micromotors based on TiO$_2$ nanotubes. Under UV light irradiation, their motion speed can get high, but the directions are difficult to control in 15% H$_2$O$_2$ solution [61].

**3.2.4 Asymmetric branches’ structures**

Asymmetric branches are always consisting of different materials in the opposite sides; under illumination, the light-driven photoelectrochemical reaction generates anions and cations at opposite ends, resulting in an asymmetric distribution of generated ions, which propels the micro/nanomotors by self-electrophoresis. Different from the nanorod, the structure of asymmetric branches can have many little branches at one end, which will benefit the chemistry reaction and generate a higher driving force.

Tang and his group created a schematic illustration of a microswimmer based on a Janus nanotree structure, in which TiO$_2$ nanowire branches are grown on a p-type silicon nanowire trunk, and in such nanotrees, the TiO$_2$ branches and the silicon nanowires work as the photoanode and the photocathode, respectively [70].
The transformation mechanisms are generally based on some typically reversible reactions including pericyclic reactions, cis-trans isomerization, dissociation processes, intramolecular hydrogen transfers and electron transfers (oxidation-reduction), which cause the alteration of physical and chemical properties involving wettabilitiy, surface free energy and liquid crystal alignment. In Figure 10, typical branched micromotor (Figure 10A) and its upgraded version (Figure 10B) are presented [70, 108]. With the shading effect of the large branched TiO₂ structures, asymmetric charge concentration will be formed around the branched structure and lead to a positive or negative phototaxis motion behavior of the micromotor.

In conclusion, compared with the single nanorod, asymmetric branches have a higher driving force in common because of a huge reaction area on the surface. In contrast, higher requirements are in need to produce such a complicated structure.

### 3.3 Various incident light wavelengths for micro/nanomotors

Light used to propel the micro/nanomotors is usually classified into three types: UV, Vis and NIR according to their wavelength. The wavelength of UV is from 10 to 400 nm, Vis is from 400 to 760 nm, while that of NIR is from 760 to 2576 nm (as shown in Figure 11) [109]. The light with different wavelengths has varied photon energy; thus, their actuation effects are expected to have an obvious difference with each other.

#### 3.3.1 NIR light

Unlike lower-frequency radio and microwave radiation, NIR electromagnetic radiation commonly interacts with dipoles present in single molecules, which changes as atoms vibrate at the ends of a single chemical bond. It is consequently absorbed by a wide range of substances,
causing them to increase in temperature as the vibrations dissipate as heat, and the same process, if run in reverse, causes bulk substances to radiate in the infrared spontaneously [110–113].

Thus, NIR is always used in photothermal-effect propulsion because of the heat generated during the reaction. Heat can not only propel micro/nanomotors to move (Figure 12A) but also provide a possibility of inactivation of cells. As we all know, most of cells cannot be alive under high temperature, so diseased cells can be killed through NIR-driven micro/nanomotors. Wu and his colleagues have put up with such a micromotor, to better observe the photothermal treatment effects [55, 59] (Figure 12B, C), with the cells labeled using propidium iodide (PI, red fluorescence labeled dead cells) after laser irradiation [58]. After being exposed to a NIR laser with enough dose, cells in contact with the micromotors appeared to be killed and undergo apoptosis, and the cytoplasm was stained red, while cells away from the motors still retained their activity and were unstained.

3.3.2 Visible light

As frequency increases into the Vis range, photons have enough energy to break the bond of some individual molecules according to the Planck-Einstein equation:

$$E = \frac{hc}{\lambda}$$  \hspace{1cm} (5)

where $h$ is the Planck constant, $c$ is the light velocity and $\lambda$ is the wavelength of light. As the wavelength of light decreases to a threshold value, electrons will be excited and then jump to the conduction bands; meanwhile, holes will be left behind in the valence bands [114–116]. Photo-excited free electrons and holes will take part into the redox reactions, generate charged ions around the motors and subsequently form an electric field, which will then drive the charged motors to move.

The most common photocatalytic materials are semiconductors and metal oxide with specific band gaps ($E_g$) that determine their light response regions, different materials have their own $E_g$ and suitable wavelength. Table 1 presents some common materials with their $E_g$ and suitable activation light wavelength. Materials with $E_g$ lower than the photon energy of Vis light are expected to absorb Vis light and drive micro/nanomotors. As an example, Figure 13A presents the BiO1/Au micromotors, which are powered by blue and even green light [72].

![Figure 12](image)

**Figure 12:** Micro/nanomotors actuated with NIR light. (A) Schematic of the NIR-driven Janus mesoporous silica nanoparticle motors with the size of hundreds nanometers [60]. Copyright 2016, American Chemical Society. (B) Schematic and snapshots of the NIR-controlled “on/off” motion for the (PSS/PAH)$_{20}$ AuNS micromotor [59]. Copyright 2015, Wiley-VCH. (C) Multilayer polymer micromotor motion controlled by the NIR laser [55]. Copyright 2014, American Chemical Society.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$ [eV]</th>
<th>(CB vs. NHE) [eV]</th>
<th>(VB vs. NHE) [eV]</th>
<th>$\lambda$ [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO$_2$</td>
<td>3.2</td>
<td>−0.29</td>
<td>2.91</td>
<td>389</td>
</tr>
<tr>
<td>MnO$_2$</td>
<td>3.6</td>
<td>−1.01</td>
<td>2.59</td>
<td>346</td>
</tr>
<tr>
<td>ZrO$_2$</td>
<td>5</td>
<td>−1.09</td>
<td>3.91</td>
<td>249</td>
</tr>
<tr>
<td>NiTiO$_3$</td>
<td>2.18</td>
<td>0.2</td>
<td>2.5</td>
<td>571</td>
</tr>
<tr>
<td>ZnO</td>
<td>3.2</td>
<td>−0.31</td>
<td>2.89</td>
<td>389</td>
</tr>
<tr>
<td>CuO</td>
<td>1.7</td>
<td>0.46</td>
<td>2.16</td>
<td>732</td>
</tr>
<tr>
<td>In$_2$O$_3$</td>
<td>2.8</td>
<td>−0.62</td>
<td>2.18</td>
<td>445</td>
</tr>
</tbody>
</table>
3.3.3 Ultraviolet

As frequency increases into the UV, photons now carry enough energy (about 3 eV or higher) to excite certain doubly bonded molecules into permanent chemical rearrangement. So, compared with Vis light, it may provide more energy to generate photo-excited electrons and thus form a stronger electric field.

In general, according to Table 2, there are more materials response to UV than Vis. Some researches shows that for some photocatalytic materials such as AgCl, only under UV or very strong Vis can the motor be propelled, which presents a better applicability of UV light [118]. Also, as indicated in Figure 13B, such motor based on TiO$_2$/Au responds to the UV light with extremely low light intensity in pure water [71]. Furthermore, TiO$_2$/Au micromotor was demonstrated to respond to Vis light with TiO$_2$ replaced by black TiO$_2$, as shown in Figure 13C [117].

![Figure 13: Light-driven micro/nanomotors actuated with UV and Vis light. (A) BIOI/Au micromotor actuated by Vis light. The “On/Off” control and the motion mean-square displacement for BIOI/Au micromotor are shown [72]. Copyright 2017, American Chemical Society. (B) Schematic illustrating the work mechanism of TiO$_2$/Au micromotor actuated by UV light [71]. Copyright 2015, American Chemical Society. (C) Visible light-driven black-TiO$_2$/Au micromotor. Mean-square displacement and schematic of the work mechanism of the micromotor [117]. Copyright 2017, American Chemical Society.](image)

### 3.4 Comparison of actuation force for light-driven micro/nanomotors

In general, those three factors introduced above all have great influence on the actuation force of light-driven micro/nanomotors. In order to gain a higher force to propel the motor, we attempted to make a comparison among all kinds of micro/nanomotors and find some potential clues for further driving force promotion of micro/nanomotors.

As shown in Tables 2–4, we have presented some examples of micro/nanomotors using those four actuation mechanisms with four kinds of structures under different light irradiation and the comparison of their velocities and actuation forces. The velocity defined here is the maximum motion speed, which is divided into two parts through different descriptions: one is the direct speed “μm/s,” and another is “bodylength/s” with a comparison...
with its own structure. The driving force is approximately evaluated by the drag force calculated through Equation 2. Besides, scale effect cannot be ignored as well. Micro/nanomotors in different scales may have different actuation mechanisms. Herein, the scale is divided into three types: micrometer scale (>1 μm), submicrometer scale (100 nm–1 μm) and nanometer scale (<100 nm). The application of different kinds of micro/nanomotors will be discussed in the next chapter.

More intuitive information of the comparison can be acquired from Figure 14. As shown in Figure 14A, B, bubble propulsion has the highest velocity and driving force in most cases, and photothermal-effect propulsion has a little lower. Another two actuation mechanisms are much lower than the top two. Besides, structure has a vital importance on the velocity and actuation force of the micro/nanomotors as well. Microspheres can decrease the resistance effectively while moving in the fluid, so the velocity is much higher, and because of the hollow structure of the tubular, bubbles can easily be released and push the motor to move ahead. Thus, nanotubulars can also have a high velocity and driving force. The motion and driving force of nanorods and asymmetric branches are considerably humble when compared with the other ones because of their relatively “heavy” structures. At micrometer scale, all these four actuation

Table 2: Comparison of motion velocity and estimated driving force for light-driven micro/nanomotors through bubble propulsion.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ZVI/Pt</td>
<td>Bubble propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>UV-Vis</td>
<td>200</td>
<td>67</td>
<td>11.3</td>
<td></td>
<td>[68]</td>
</tr>
<tr>
<td>Ag-ZIF</td>
<td>Bubble propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>UV</td>
<td>310</td>
<td>3.4</td>
<td>263</td>
<td></td>
<td>[67]</td>
</tr>
<tr>
<td>TiO₂/Pt</td>
<td>Bubble propulsion</td>
<td>Nanotubular</td>
<td>Submicro</td>
<td>UV-vis</td>
<td>35</td>
<td>233</td>
<td>0.66</td>
<td></td>
<td>[66]</td>
</tr>
<tr>
<td>AuNP/PANI/Pt</td>
<td>Bubble propulsion</td>
<td>Nanotubular</td>
<td>Micro</td>
<td>UV-Vis</td>
<td>88.7</td>
<td>4</td>
<td>16.7</td>
<td></td>
<td>[63]</td>
</tr>
<tr>
<td>Am-TiO₂/Au</td>
<td>Bubble propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>UV</td>
<td>101</td>
<td>5</td>
<td>19</td>
<td></td>
<td>[65]</td>
</tr>
<tr>
<td>TiO₂</td>
<td>Bubble propulsion</td>
<td>Nanotubular</td>
<td>Micro</td>
<td>UV</td>
<td>5.39</td>
<td>1.8</td>
<td>0.20</td>
<td></td>
<td>[61]</td>
</tr>
<tr>
<td>Carbon/Pt</td>
<td>Bubble propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>UV-Vis</td>
<td>500</td>
<td>50</td>
<td>471</td>
<td></td>
<td>[95]</td>
</tr>
<tr>
<td>TiO₂</td>
<td>Bubble propulsion</td>
<td>Nanotubular</td>
<td>Micro</td>
<td>UV</td>
<td>324</td>
<td>4</td>
<td>244</td>
<td></td>
<td>[64]</td>
</tr>
<tr>
<td>TiO₂/Au/Mg</td>
<td>Bubble propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>UV</td>
<td>80</td>
<td>5</td>
<td>12.1</td>
<td></td>
<td>[62]</td>
</tr>
</tbody>
</table>
mechanisms can exist, and most of structures are fabricated in this size. However, when the scale is declined to the submicrometer scale, bubble propulsion could hardly occur, because of this, the size of the tubular cannot be designed to be too small. Otherwise, bubbles will not generate inside the tubular and propel the motor. When the size comes to the nanometer scale, only microspheres can be fabricated in such a tiny size, and electrophoretic propulsion would be the main actuation mechanism of micro/nanomotors.

Besides, there are some other factors deserved to be paid attention to, such as loading amount, concentration of liquid, or easiness of control. However, it is not easy to evaluate all those factors because there is no suitable standard for us to analyze them, and some important information is scarce. For example, about the easiness of control, it is not easy to define how easy or difficult the control is because of insufficient professional judging standard.

### Table 3: Comparison of motion velocity and estimated driving force for light-driven micro/nanomotors through photothermal-effect propulsion.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Actuation mechanism</th>
<th>Structure</th>
<th>Scale</th>
<th>Light</th>
<th>Velocity $[\mu m/s]$</th>
<th>Velocity $[\mu m/s]$</th>
<th>Driving force $[pN]$</th>
<th>Appearance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAH/PSS</td>
<td>Photothermal-effect propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>NIR</td>
<td>220</td>
<td>22</td>
<td>20.7</td>
<td></td>
<td>[56]</td>
</tr>
<tr>
<td>PAH/PSS</td>
<td>Photothermal-effect propulsion</td>
<td>Nanotubular</td>
<td>Micro</td>
<td>NIR</td>
<td>150</td>
<td>19</td>
<td>11.3</td>
<td></td>
<td>[59]</td>
</tr>
<tr>
<td>CHI/ALG</td>
<td>Photothermal-effect propulsion</td>
<td>Nanorod</td>
<td>Micro</td>
<td>NIR</td>
<td>23.3</td>
<td>7.7</td>
<td>3.38</td>
<td></td>
<td>[57]</td>
</tr>
<tr>
<td>PSS/PAH/Au</td>
<td>Photothermal-effect propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>NIR</td>
<td>42</td>
<td>4.2</td>
<td>3.96</td>
<td></td>
<td>[58]</td>
</tr>
<tr>
<td>PLL/BSA/AuNps</td>
<td>Photothermal-effect propulsion</td>
<td>Nanotubular</td>
<td>Micro</td>
<td>NIR</td>
<td>68</td>
<td>5.2</td>
<td>6.41</td>
<td></td>
<td>[39]</td>
</tr>
<tr>
<td>AuNS</td>
<td>Photothermal-effect propulsion</td>
<td>Microsphere</td>
<td>Nano</td>
<td>NIR</td>
<td>6.4</td>
<td>40</td>
<td>0.01</td>
<td></td>
<td>[60]</td>
</tr>
<tr>
<td>PtNP/AuNS</td>
<td>Photothermal-effect propulsion</td>
<td>Nanotubular</td>
<td>Micro</td>
<td>NIR</td>
<td>52</td>
<td>3.5</td>
<td>4.9</td>
<td></td>
<td>[55]</td>
</tr>
</tbody>
</table>

4 **Motion control of micro/nanomotors**

Motion control of light-driven micro/nanomotors has been a problem that is very much bothering the academics during the recent years. We can control objects in a macroscopically precise manner, but it is not easy at microscale. First of all, artificial chips cannot be fabricated in a very tiny scale and inserted inside because of the limitation of technology, so some conventional methods will not be suitable. Also, at the microscale, a little interference may lead to a large deviation. In order to confirm the stability of motion, better strategies of motion control are of vital importance. Besides the direct control of light, magnetic field is used frequently to guide the motion and some other methods, including acoustic field and electric field, are adopted in the last few years to assist the motion control of light-driven micro/nanomotors.
Table 4: Comparison of motion velocity and estimated driving force for light-driven micro/nanomotors through self-electrophoretic propulsion and osmotic propulsion.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO₂/Au</td>
<td>Self-electrophoretic propulsion</td>
<td>Microsphere</td>
<td>Nano</td>
<td>UV</td>
<td>48.5</td>
<td>48.5</td>
<td>0.46</td>
<td></td>
<td>[77]</td>
</tr>
<tr>
<td>Gold/iron oxide</td>
<td>Self-electrophoretic propulsion</td>
<td>Nanorod</td>
<td>Submicro</td>
<td>UV</td>
<td>30</td>
<td>15</td>
<td>0.28</td>
<td></td>
<td>[76]</td>
</tr>
<tr>
<td>Cu₂O-Au</td>
<td>Self-electrophoretic propulsion</td>
<td>Microsphere</td>
<td>Sub micro</td>
<td>Vis</td>
<td>6.9</td>
<td>3.5</td>
<td>0.13</td>
<td></td>
<td>[74]</td>
</tr>
<tr>
<td>Si-Au</td>
<td>Self-electrophoretic propulsion</td>
<td>Nanorod</td>
<td>Micro</td>
<td>UV-Vis</td>
<td>5</td>
<td>1</td>
<td>0.19</td>
<td></td>
<td>[75]</td>
</tr>
<tr>
<td>TiO₂/Pt/Si</td>
<td>Self-electrophoretic propulsion</td>
<td>Asymmetric branches</td>
<td>Micro</td>
<td>UV-Vis</td>
<td>5.6</td>
<td>0.56</td>
<td>0.53</td>
<td></td>
<td>[70]</td>
</tr>
<tr>
<td>p-Si/Pt</td>
<td>Self-electrophoretic propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>Vis</td>
<td>12.5</td>
<td>0.4</td>
<td>7.07</td>
<td></td>
<td>[69]</td>
</tr>
<tr>
<td>TiO₂-Au</td>
<td>Self-electrophoretic propulsion</td>
<td>Microsphere</td>
<td>Submicro</td>
<td>UV</td>
<td>25</td>
<td>17.9</td>
<td>0.33</td>
<td></td>
<td>[71]</td>
</tr>
<tr>
<td>Iron oxide</td>
<td>Self-electrophoretic propulsion</td>
<td>Nanorod</td>
<td>Micro</td>
<td>Vis</td>
<td>4.5</td>
<td>2.5</td>
<td>0.085</td>
<td></td>
<td>[42]</td>
</tr>
<tr>
<td>BiOI</td>
<td>Self-electrophoretic propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>Vis</td>
<td>2.6</td>
<td>1.3</td>
<td>0.049</td>
<td></td>
<td>[72]</td>
</tr>
<tr>
<td>TiO₂/SiO₂</td>
<td>Self-electrophoretic propulsion</td>
<td>Microsphere</td>
<td>Submicro</td>
<td>UV</td>
<td>6</td>
<td>3</td>
<td>0.113</td>
<td></td>
<td>[73]</td>
</tr>
<tr>
<td>Pt-g-C₃N₄</td>
<td>Osmotic propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>UV-Vis</td>
<td>23</td>
<td>9.6</td>
<td>0.520</td>
<td></td>
<td>[80]</td>
</tr>
<tr>
<td>TiO₂</td>
<td>Osmotic propulsion</td>
<td>Microsphere</td>
<td>Micro</td>
<td>UV</td>
<td>6.6</td>
<td>5.5</td>
<td>0.075</td>
<td></td>
<td>[78]</td>
</tr>
</tbody>
</table>
4.1 Light control

As the name suggests, we can control the light directly to guide the motion of micro/nanomotors by tuning the intensity of light, the “on/off” status of light, the incident light direction and the wavelength of light.

There are many experiments presenting that the speed of motion increases proportionately with the light intensity because of the higher speed of the chemical reaction [79, 80]. As demonstrated in Figure 15A, B, the motion velocity shows a nice linear dependence on the light irradiation intensity [74, 75]. The motion occurs upon light activation; after reaching the destination, the motion will be stopped through withdrawing the incident light; and when light is applied in an opposite direction, the micromotor will return back and stop when light is off, showing a great control of the “on/off” switch. Besides, the micromotor can be programmed to move in a controllable manner along the designed trajectory, as displayed in Figure 15C. The motion’s start and stop are controlled through the application and withdrawal of light, while the direction control is achieved by changing the direction of incident light. For the wavelength of light, because of different materials have a different response to NIR, Vis and UV light irradiation [119], Tang and his group improved their original design by dye modification on the TiO2 branches. As the dye-sensitized microswimmer can be propelled by the light absorption of dye molecules, the spectral response of the microswimmer is determined by the spectral response of the corresponding dye-sensitized solar cell in Figure 15D [70].

4.2 Magnetic field assisted control

As an assisting method, magnetic control of the directionality of the light-driven micro/nanomotor can be achieved through the deposition of some magnetic materials such as Ni, Fe3O4 and NbFeB. Generally, magnetic field is generated by two couples of coils in orthogonal directions. When an alternating current is applied to the coils, a changing magnetic field will generate and thus control the motion direction of light-driven micro/nanomotors.

Because of the extremely tiny size of the structure, it is hard to add too much magnetic materials into the motor; therefore, sometimes the magnetic force is a little low. Because of the low actuation force, several motion styles, including stick-slip, rotating and freestyle swimming, are developed for magnetic field control. Figure 16A presents an example of light-driven micro/nanomotors with Fe2O3 integrated for magnetic control [76]. As illustrated in Figure 16B, a very thin layer of Ni is coated on the microsphere, and while under the magnetic field, it will follow predetermined trajectories to execute a precisely controlled motion. With a thin layer of iron (50 nm), the micromotor follows a trajectory with a high precision of magnetic control (Figure 16C) [120].

4.3 Comparison of different control approaches

In order to gain a more precise control of motion, it is necessary to choose a suitable control strategy. As introduced above, pure light control is relatively easy to control the velocity of micro/nanomotors just by adjusting the light intensity and through the “on/off” switch to start or stop the motion, but so as to control the moving direction, we need to change the position of light source. However, it is far from easy to put the light source anywhere we want, and the positive or negative phototaxis of motor cannot be accurate enough to ensure the motion directly to/opposite to the light source.
When a magnetic field is added to assist the control, the motion direction control of light-driven micro/nanomotors can be much easier; just by adjusting the intensity and direction of electric current in the coil, a suitable magnetic field can be generated to control the motion direction of micro/nanomotors, which is much more convenient and precise than changing the position of the light source. However, it is of vital importance to integrate some magnetic materials into the motor, which may require some advanced equipment, and extra space is required to place the magnetic field generating device.

As for other control mechanisms, more and more novel strategies are put forward during the recent years such as the pH control [121] or electrostatic control [122], but the main problem has not been changed ever: how to achieve a precise control in complex surroundings. Because of the limitation of the technology, we cannot have a very accurate control on those variables such as temperature or acoustic wave. It is still a great challenge for us to overcome.

5 Conclusions and outlook

In this review, we have presented an overview of light-driven micro/nanomotors in the past two decades. Compared with other kinds of propulsion approaches including acoustic, magnetic and electric field, light has its unique advantages such as low cost and it is easy to control under light and to conduct some complex tasks. Light-driven micro/nanomotors are of great potential in the exploration and application at the micro/nanoworld and have been witnessed to be applied into environment remediation, biological field and micro engineering. The emerging applications for micro/nanomotors put up the request on the driving force and motion control. There are three
main factors influencing the actuation force of motion significantly: actuation mechanism, structure and the light wavelength. In order to gain a high actuation force, bubble propulsion and the structure of microsphere under UV light irradiation are expected to be a much better combination than others. Besides, owing to the more and more complex tasks requirement, precise control is essential as well. Light control includes the light intensity, “on/off” switch and the position of light source, which can effectively guide the motion but not as precise as required. While by adding a magnetic field to assist the control, the whole process can be controlled more conveniently and accurately.

Figure 15: Micro/nanomotors’ motion controlled by light irradiation. (A) and (B) present the dependence of micro/nanomotors’ motion speed upon light intensity for Cu₂O/Au and Si/Au micromotors, respectively [74, 75]. Copyright 2017, The Royal Society of Chemistry. (C) Motion direction controlled by the incident light directions for TiO₂ micromotor [78]. Copyright 2016, Wiley-VCH. (D) Schematics of the asymmetric branched Si/TiO₂ micromotor alignment mechanism with side illumination and its following of the “nano” shape navigated by light [70]. Copyright 2016, Nature Publishing Group.
In order to accomplish the task more efficiently and conveniently, for example, for environment remediation, light-driven micro/nanomotors are required to move automatically to those seriously polluted areas at a high speed. Bubble propulsion, as a most commonly used actuation mechanism, because of its random motion and high actuation force, has been widely acknowledged all over the world. Whereas for biomedical applications, because of the fast motion, directional control and tissue penetration ability of the photothermal-effect propulsion, it is widely used. The motor not only can deliver the drug but also can kill the diseased cells under the high temperature surrounding of the motor. As for cargo delivery, precise control is of vital importance; self-electrophoretic propulsion and osmotic propulsion with an accurate control strategy such as magnetic control will have a better application prospect.

However, there are still some existing challenges, which influence very much the development of micro/nanomotors. Even though the potential of light-driven micro/nanomotors seems enormous, until now, only a few successful applications have been reported; high cost and the limitation of environment are the major obstacles. Conversely, the actuation force is not high enough to achieve a very fast motion. Controlling the attitude of the motors while moving, which is necessary in a lot of micro-object delivery task, is almost blank in the presently reported research work. Thus, light-driven micro/nanomotor is still at its baby stage, and plenty of unprecedented and exciting work is to be done.

Through this review of light-driven micro/nanomotors, the further application of micro/nanomotors is still faced with the contradiction between high driving force and biocompatibility. So as to bridge this gap, bubbles generated through artificial water splitting technology can be adopted into light-driven micro/nanomotors. As artificial water splitting with relatively high efficiency was already realized in nearly pure water [123, 124], it is of great potential to manipulate biological samples, including living cells, in viscous cell culture medium with light-driven micro/nanomotors through a combination of artificial water splitting and micro/nanomotors.

As for future light-driven micro/nanomotors, we believe that they will be combined with the artificial intelligence in the Information age. The chip will be fabricated at micro/nanoscale and integrated into the motors to facilitate them to perform more complex tasks. For example, in drug delivery, it can move automatically to find where is in need of drug through a microsensor and move there swiftly as well as release the drug. Also, in the application of environment remediation, motors can not only choose their moving routines more intelligently but also

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**Figure 16:** Control of magnetic field. (A) Magnetic moment measured for the Au/Fe$_3$O$_4$ micromotor and its motion trajectory in 2.5 V% H$_2$O$_2$ solution under magnetic field control [76]. Copyright 2017, The Royal Society of Chemistry. (B) Schematic of the magnetic control of multilayer Ir-TiO$_2$-Ni-Ti-SiO$_2$ Janus micromotor and time lapse images showing the magnetically guided propulsion of the micromotor in the presence of extremely low concentration of hydrazine [79]. Copyright 2014, American Chemical Society. (C) Schematic of the Fe/TiO$_2$ Janus micromotor and its controlled motion trajectory with assisted magnetic field [120]. Copyright 2018, Elsevier.
store the solar energy while under the light irradiation in order to move in the night without any energy input, which will ensure that the motors move continuously and decontaminate seas, lakes and rivers day and night. Whereas in cargo delivery, better accuracy and stability as well as faster speed are of vital importance. When there will be a management system to control all the motions of the micro/nanomotors, automated transportation will be achieved. Light-driven micro/nanomotors are beginning to lighten up the future of human beings by serving as a tiny doctor working in biomedicine and disease diagnosis, manufacturing microscale devices from the bottom nanoworld and protecting our home, Earth, through purifying our waters incessantly.

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References


[81] Ti conflict: Zhan et al.: Recent advances of light-driven micro/nanomotors


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**Bionotes**

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