Origami Inspired Soft Micro/Nano-robotics.

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Abstract

Microrobotics and nanorobotics have the potential to perform many tasks in important biomedical applications. These micro/nano-machines are capable of propulsion at low Reynolds number fluidic environments by an external rotating magnetic field. For decades, roboticists have focused their efforts on rigid systems that enable programmable, automated action, and sophisticated control with maximal precision and speed. Meanwhile, it is also critical to develop new soft and flexible architectures and potential modes that are small, soft, adaptive, and stimuli-responsive, for the structure and kinetic optimization. In this report, by combing the concepts from micro/nano-robotics and stimuli-responsive shape-shifting materials, scientists designed some ‘smart’ robotics known as Origami Inspired Soft Micro/Nano-robotics, with its potential fabrication and control methods. This origami inspired soft small scale magnetic robots are capable of efficient propulsion at low Reynolds numbers and cargo delivery. This new micro/nano-robotics mechanism and its attractive performance could provide guidance toward prospective practical design for biomedical operation at the micro/nano-scale.

Key words: magnetic micro/nano-robotics, origami, soft, stimuli-responsive, shape-shifting, magnetic control, biomedical, cargo delivery, low Reynolds number.

1. Introduction

Up to date, the majority of robots are electronically driven rigid and hard machines that requires external power sources, preprogramming is needed to perform even simple tasks, lacking of flexibility and adaptability. Some great challenges in conventional robotics relate to scaling down in size and difficulties in adaptivity in motion. To face the first challenges, microrobots and nanorobots that can be steered by external energy sources (e.g. laser light, ultrasound, electrical fields, magnetic fields, or combinations of them[1-6]in low Reynolds numbers[7] has been developed these twenty years. These small scale robots have been popularly conceptualized for biomedical applications[8-10], such as navigating in the human blood vessel and capable of precise targeting drug delivery[11]. As for the second challenge, soft-robotic with soft materials provided additional degrees of freedom (DOF) for continuous actuation and shape change, allowing soft robot to adapt to unpredictable obstacles. These soft-robotics have been used to reduce control complexity and manufacturing cost of robots, while enabling sophisticated and novel functionalities often in direct contact with rigid and hard robotics[12].

Usually, micro/nano-robot is rigid and hard, great efforts are being made to optimize the geometric design of rigid micro/nanorobotics. Studies have been done in optimizating the geometric design of micro/nano-robotics[13-18], which indicates that chubby skew-symmetric shape[13], geometrically achiral planar structures[14] and bioinspired microrobot with spherical/tubular head and cilia/helical tails[17] can be efficiently propelled in low Reynolds number by a rotating magnetic fields. However, compared to the rigid and hard small-scale robots, robots made from soft materials have less dense, higher biodegradability, higher resorbability, and better deformation properties[1,18,19]

Nature uses various activation to program complex transformation in the shape and functionality of living organisms. And there also an ancient art of paper folding in Japan known as origami, which allows the transformation of two dimensional (2D) patterns into three dimensional (3D) shapes.

The principle of the origami mechanism becomes an interesting and fast growing field. Famous designers such as Robert J. Lang, Meguro Toshiyuki, Jun Maekawa and Peter Engel has been studied the principle of origami tens of years and they using crease patterns to create complex and super-complex origami models, while a crease pattern is an origami diagram that consists of all or most of the creases in the final model, rendered into one image.

So, inspired by the ancient art of paper folding – ‘origami’, researchers can applied the concept of origami and kirigami to design a variety of foldable or stretchable micro/nano-structures[19-26], and to explore new locomotion mechanisms of micro/nano-robotics, which can be useful in biomedical applications.

Many works have been done to develop multi-scale origami inspired micro/nano-robotics model for the targeting magnetic control, in order to apply them in biomedical applications like targeting drug delivery. Designs of some origami-inspired micro-robotics, the possible fabrication and deformation-control methods of micro-robotics, and some previous published study (Tottori, 2018) [27]assessed the swimming mechanism of L-shape micro-robotics in a precessing magnetic field, showing that these L-shape micro-swimmers could swim forward in a cork-screw fasion along the precession axis.

1). Micro-scale origami-inspired robotics.

Whilst some research has been carried out on some micro-scale origami-inspired structures and shows that it is feasible to fabricate such micro-structures as well as successfully stimulate them to change their shapes, there have been few empirical investigations into the field of origami-based micro-robotics. In this section, I present a few origami mechanisms that can be used in the design of micro/nano-robotics. Below shows some origami designs of mine. Time-lapse images of two origami design shown in Figure 1 (see GIF S1-2, Supporting Information). The folded L-shape CAD are shown at the left hand, the crease pattern of the unfolded design are shown at the right hand, both of them are not drawn to scale.. The red line means mountain fold, which is a fold that is facing upwards; and blue one means a valley fold, which is a fold downwards.

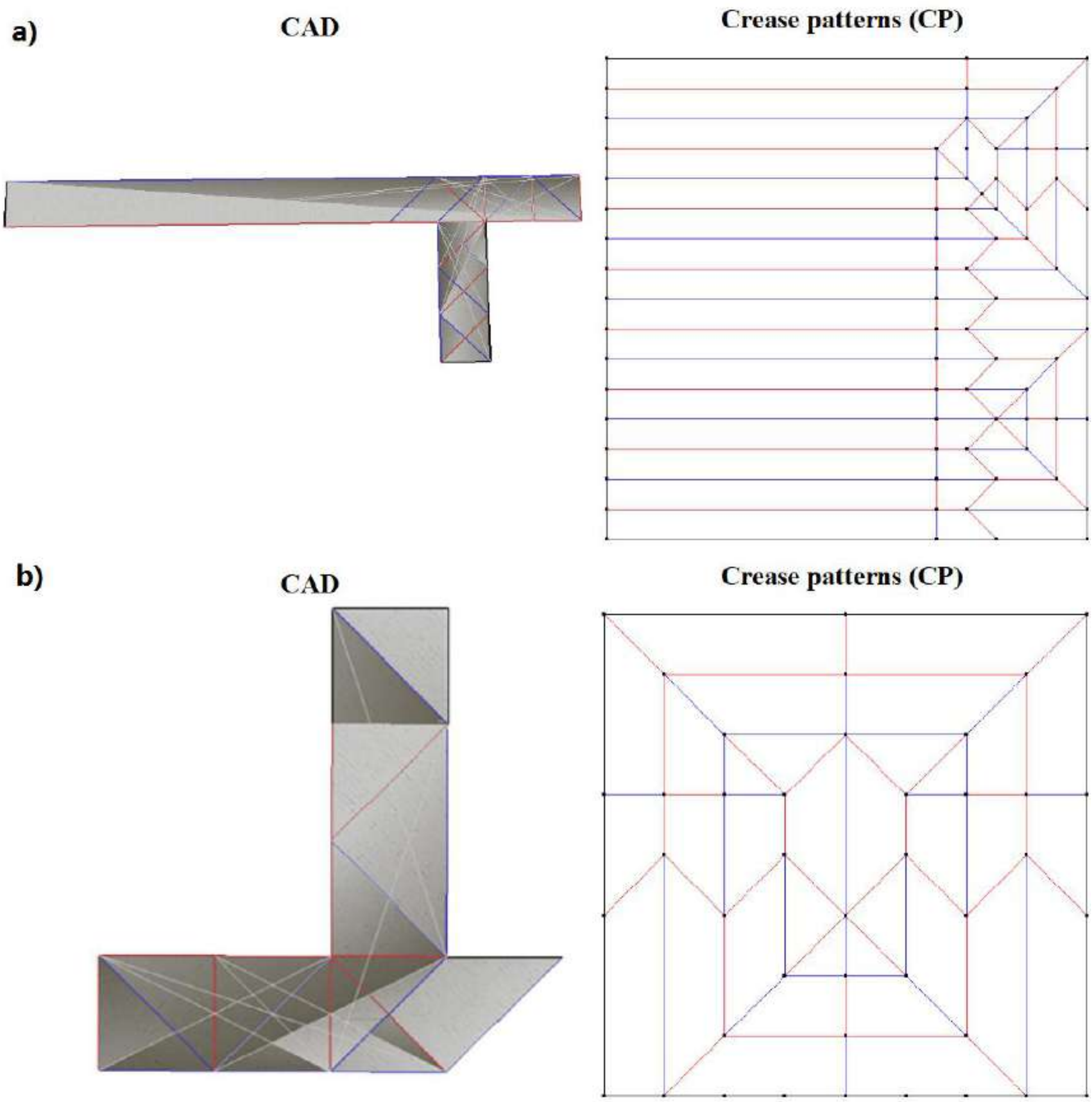

Figure 1. My designs of two L-shape origami mechanism.

2). Possible fabrication and deformation-control methods of origami inspired micro-robotic.

The problem of the fabrication and deformation methods for the origami has been extensively studied. Gracias's study (2010) [28] describes the fabrication process of patterned polyhedra which having 100±300 μm sides is folded from two-dimensional (2D) structures under the influence of the surface tension of liquid solder. The approach they demonstrate has four steps: 1) The desired structures are designed in planar form as a series of unconnected but adjacent faces. 2) The faces are fabricated in 2D on a sacrificial layer using a combination of photolithography, evaporation, etching, and electrodeposition. 3) The ensemble of faces is covered with a thin film of liquid solder by dip coating. 4) The structure is released from the substrate by dissolving the sacrificial layer, and allowed to fold under the influence of the surface tension of the molten solder. This strategy is sketched in Figure 2, which can be used for the

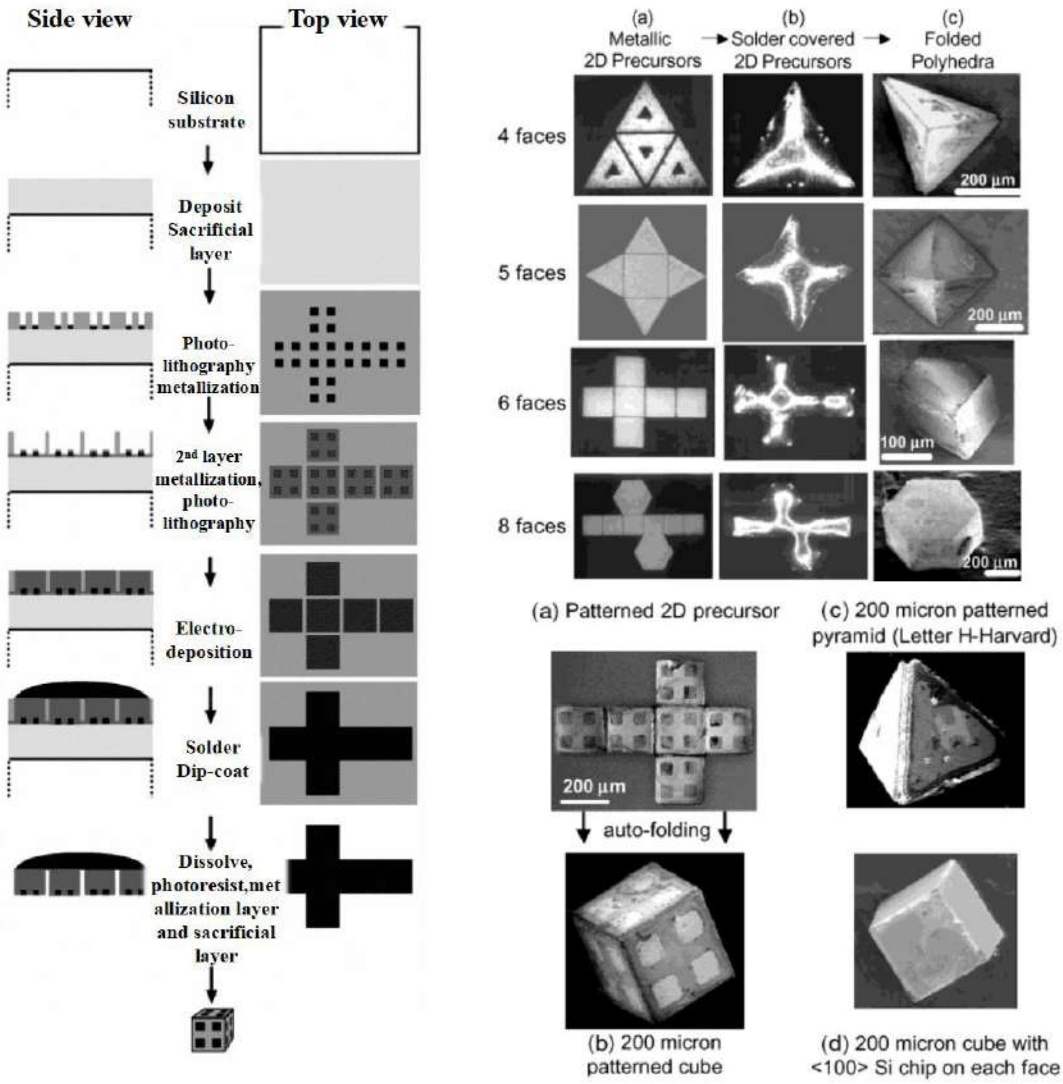

Figure 2. Basic steps involved in the fabrication of patterned polyhedra including a) depositing a sacrificial layer on a silicon substrate, b) defining the pattern by photolithography followed by evaporation of a metallic layer, c) dissolving the first layer of photoresist, evaporating a seed layer of metal for electrodeposition, and patterning a second layer of photoresist with the boundary of each face of the polyhedron in registry with the pattern already present, d) electrodeposition to build each face, e) solder deposition by dip-coating, f) dissolution of photoresist, metallization layers, and sacrificial layer to release the structure from the substrate, g) heating the 2D structure above the melting point of the solder which causes it to fold into a 3D polyhedron, due to minimization of the surface area of the molten solder.

Previous study (Figure 3a) [29] shows that the strain gradient along the thickness direction can be controlled through temperature, frequency, composition and deposition rates etc, associated with the thin-film deposition process. This strategy using capilary forces, thin-film residual stresses or active materails, can produce mesostructures with tubular, scroll-like or polyhedral geometries, in a range of material systems.

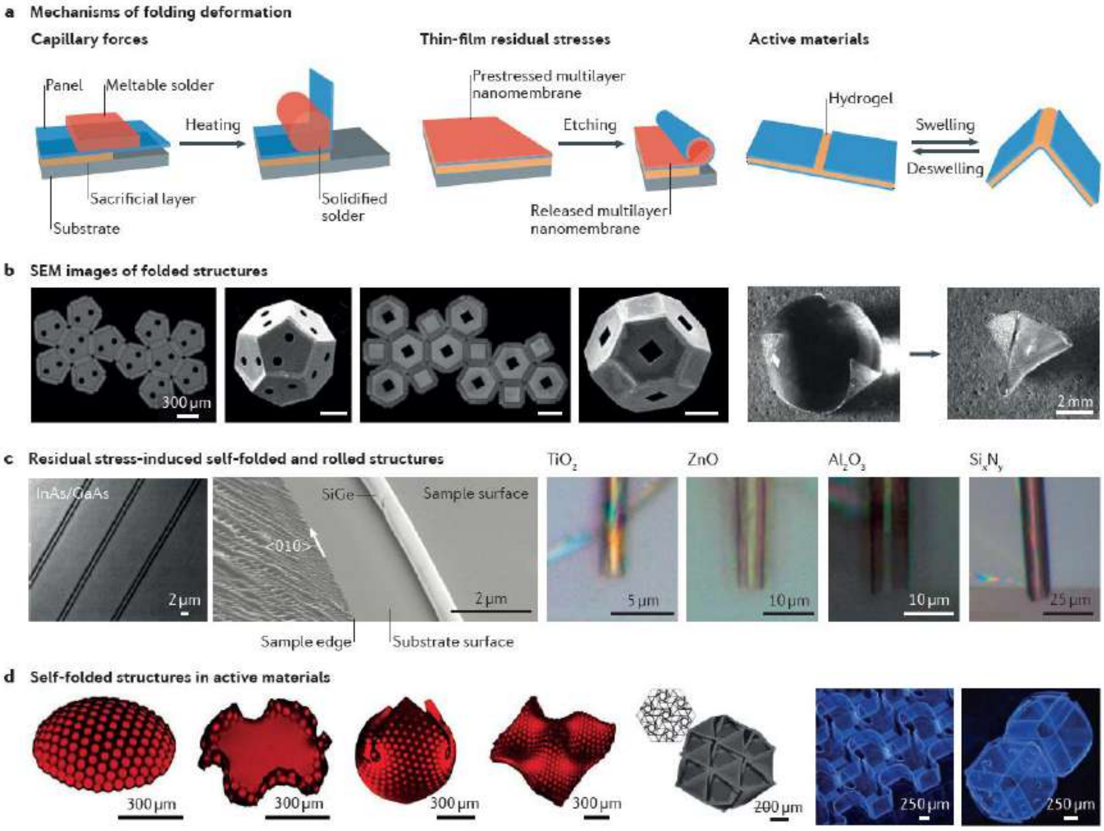

Figure 3. Micro and nanoscale origami: schemes, structures and device applications. a) Schematic illustrations of methods that rely on capillary forces (left), thin-film residual stress (middle) and active materials (right). b) Optical and scanning electron microscope (SEM) images of folded structures formed using capillary forces, including a dodecahedron and an octahedron of nickel, and a tetrahedron of polydimethylsiloxane. c) Optical and SEM images of residual-stress induced self-folded or rolled structures in a range of materials. d) Self-folded structures in active materials: hydrogels (left five images) and photopatterned polymers (right two images).

Rauch, et al.[30], proposed their work about the smallest microhouse in the world, which is inspired by the origami mechenism, and can be assembled on the facet of an optical fiber. This could be a novel methods for the fabrication and assembly of micro/nano-robotics.

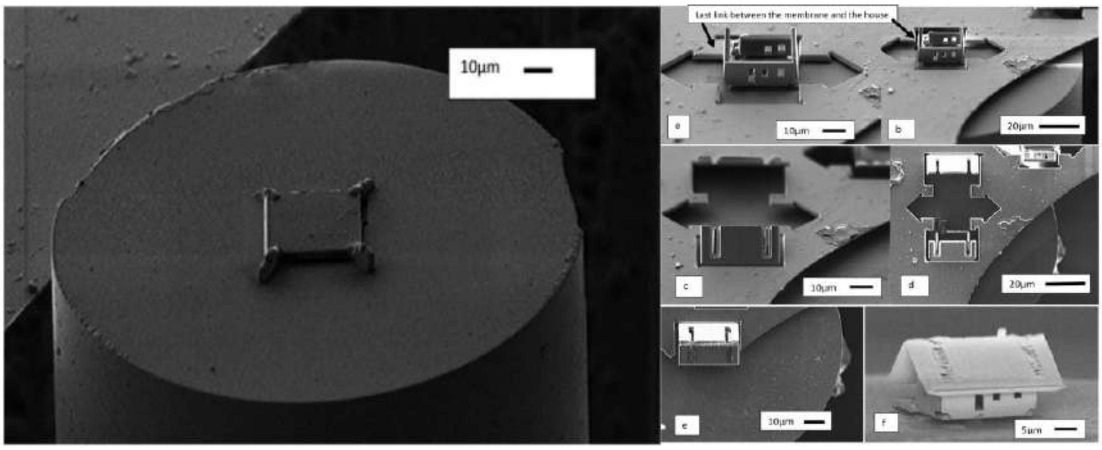

Figure 4. (Left) Microhouse assembled by origami and welded on top of the facet of an optical fiber in a SEM and FIB dual beam. (Right)(a) After the step of welding of the base of the microhouse on the facet of the optical fiber, we must cut the thin last link between the base of the

microhouse and the membrane. During the assembly time and the welding time, the stability of the system is very important. In the case of drift of the robot, the microhouse could be broken. (b) The link is cut, and we can extract the microhouse by the background direction. [(c) and (d)] After patterning and self-folding the first roof at 35°, we install the microhouse from the background like “mortise and tenon.” This step requires a very high accuracy less than 10 nm. (e) After welding the first roof, we install the second roof under the same conditions and we realize the welding step always with naphthalene gas. This step also requires accuracy and stability. (f) After welding the two roofs, we built the chimney. This picture was realized with the ESB detector. The other pictures were always realized with the SE2 detector.

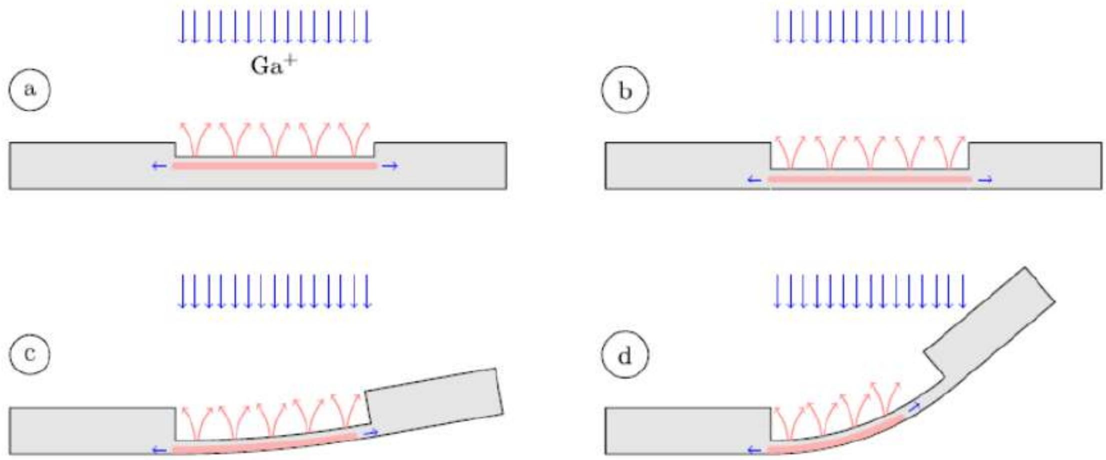

Figure 5. (Color online) Theory of the origami process: (a) The first step of this process corresponds to a sputtering with gallium ions of the interesting area. (b) When the bulk of the link between the membrane and the panel to fold corresponds to a specific thickness, a bimetallic strip appears. (c) The effect of sputtering produces a differential dilatation coefficient into the upper part in white and the down part in red of the link. (d) The panel self-fold from 0° to 90°.

3). Magnetic control method for the micro/nano-robotics.

A simple analytical approach (Tottori, 2018. [27]) shows that a precessing field can introduce dynamic chirality into the swimming motion of 2D structures.With a magnetic field, the L-shape 2D structure exhibits a certain magnetization **M**. The magnetic torque is $T = \mu_0 M \times H$ as the field rotates, where H is the external field and μ_0 is the permeability of free space. Moreover, the external force F, torque T, translational velocity V, and rotational velocity Ω are related as below:

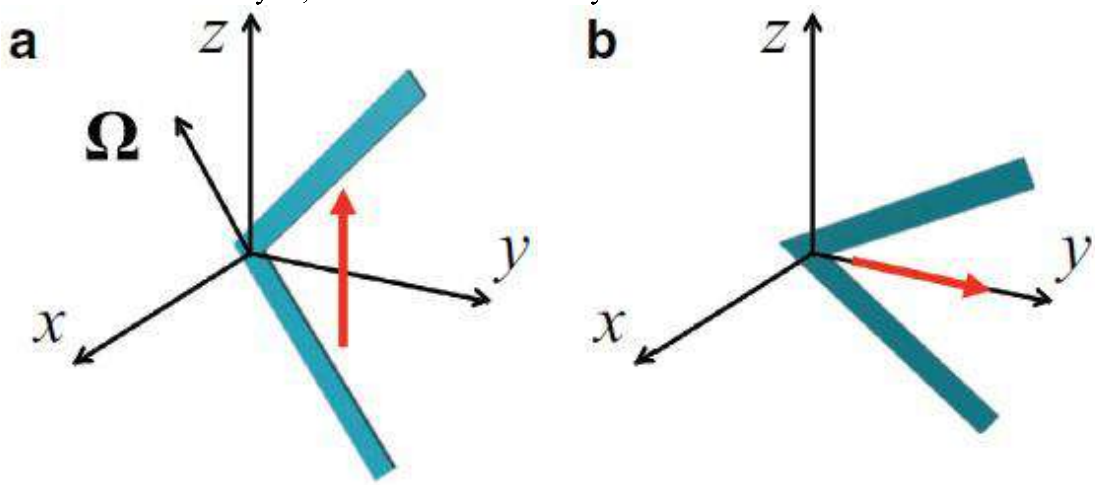

Figure 6. Schematic view of 2D swimmers with bend angles of a) 90 ° and b) 60 ° in a Cartesian coordinate system. Red arrows indicate the directions of easy axes.

The propulsion matrices **A**, **B**, and **C** of the 2D structures in **Figure 6**a,b are given by:

$$\mathbf{A}=\begin{bmatrix} A_1 & 0 & 0 \\ 0 & A_2 & 0 \\ 0 & 0 & A_3 \end{bmatrix},\mathbf{B}=\begin{bmatrix} 0 & 0 & B_{13} \\ 0 & 0 & 0 \\ B_{31} & 0 & 0 \end{bmatrix},\mathbf{C}=\begin{bmatrix} C_1 & 0 & 0 \\ 0 & C_2 & 0 \\ 0 & 0 & C_3 \end{bmatrix}$$

F = 0 since there’s no external force exhibit, and the direction of the forward swimming velocity is collinear with the precession axis. Thus, the forward swimming speed is:

$$|v_f|=\frac{|\mathbf{V}\cdot\mathbf{\Omega}|}{|\mathbf{\Omega}|}=\left|\left(\frac{B_{13}}{A_1}+\frac{B_{31}}{A_3}\right)\Omega_1\Omega_3\right|$$

which means that the rotational axis must have components in both the x- and z-directions. The wobbling angle can be tuned independently of the applied rotational frequency when it meets the minimal geometric requirement for the swimmer, which is (B13/A1+B31/A3 $\neq$ 0).

4. Considerations for Societal, Environmental or Ethical Impacts

China Association for Science and Technology has released 60 major scientific and engineering problems in 12 fields(May 20th , 2018), including the field of micro/nano-robotics.

The market potential of nanomedicial is huge. According to the investigation of the Cancer Statistics in China (2017)[31], The total market scale of cancer medicine, including colorectal cancer, gastric cancer, liver cancer and coronary heart disease，which has hte highest desease rate, is about 13.7 billion yuan (Figure 7). While the estimated global market size of nanodrugs for cancer treatment is about 134.4 billion dollars in 2017, and it is expected to grow into 300.0 biillion dollars in 2021. Based on the data mentioned above, the author drawn the figure 8, which shows the estimated total market size for surgical robotics in China, 2017.

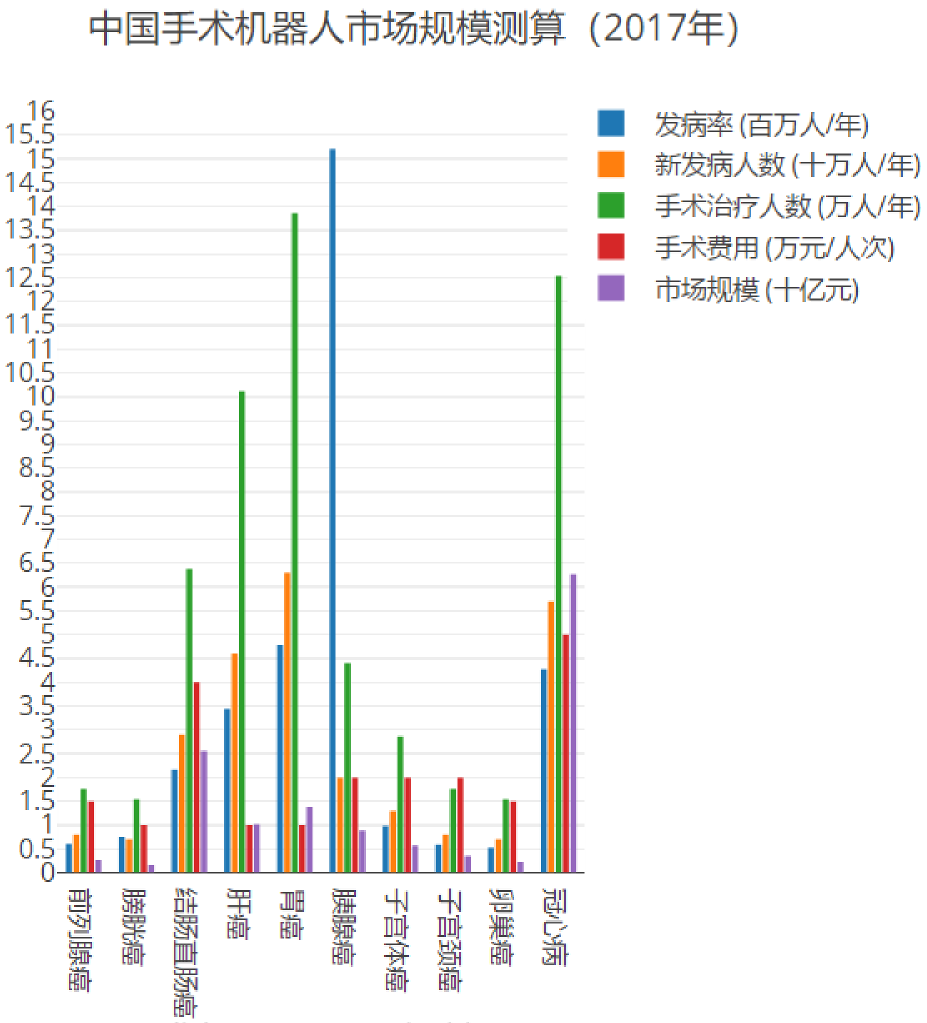

Figure 7: Investigation of cancer desease. (Image: Jiyu Xie)
(Data source: Cancer Statistics in China, 2017.[31])

There also has many favorable policies in China in encouraging the development of micro/nano-robotics system for medical use. For example, "Made in China 2025" is putting forward in the field of biomedicine and high-performance medical instrument development in view of new products of chemical drugs, including new mechanism and new targets for chemical drugs and personalized treatment. And the goal of “Healthy China 2030” is to provide health services to every citizen by 2030. Life expectancy is to reach 79 years old, aimed at meeting the standard of high-income countries.

Thus we can see the promising future of the micro/nano-robotics, which can be used as an alternative to chemotherapy for cancer treatment. The traditional cancer treatment kills not only cancer cells but also the healthy human cells, which is also unexpected, while the micro/nano-robotics would seek out for cancer cells and destroy them, dispelling the disease at the source, leaving healthy cells untouched. Such requirments can be met by the smicro/nano-scale drug delivery systems mamufactured by micro/nano-technology. Micro/Nano-robotics has incredible potential for revolutionizing therapeutics and diagnostics under the premise of developing ingenious micro/naon-devices, and the most promising application of targeting drug delivery can be done using these tiny machines. These micro/nano-robotics nanomedicines can boldly go where traditional drug hasn't gone before. With the micro/nano-robotics, therAprutic agents can be carried on their surfaces, which can be driven to the target tissure or organ under an external rotating magnetic field.

Micro/Nano-robotics for diagnosis, treatment, and monitoring diseases is a fast-developing area of biomedical research and its amalgamation with engineering, pharmaceutical, and medical sciences will become the order of the day in the years to come. In any case, the responsible application of micro/nano-robotics to medicine boasts hopes for extending the human lifespan and improving quality of life.

But it is also essential to ensure that any nanomedical techniques are a) safe, b) effective, c) ethical, d) not misused and e) not exploited. Then responsible application of these technologies may lead to better ways to prevent, diagnose, and treat neurological and behavioral disorders which would dramatically change the world for the better.

5. Conclusions

Nature is inspirational for the creation of more adaptive micro/nano-robotics which can move efficiently in fluids at low Reynolds number. In the specific case of self-folding, designing the corresponding 2D patterns which according to the stimulus will configure the desired 3D geometry. But the design of those origami-like structures still remains very challenging. Inspired by the ancient art of paper folding - ‘origami’, scientists designed some origami-inspired micro-robotics mechanisms and demonstrated the possible fabrication and deformation-control methods of micro-robotics. The magnetic controled swimming mechanism of L-shape micro-robotics showing the swimming capability of these L-shape micro-swimmers. The future work will focusing on the optimization of the geometric design, the fabrication process, the self-assembly strategy and the precise control method. The therapeutic goals for the development of these medications basically is to deliver less medication to targeted tissues only, resulting in more effective treatment with fewer adverse effects.

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