FERROMAGNETIC SOFT ROBOT BIO-MIMETICALLY INSPIRED

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Nature has adapted to allow the survival of its species through the development of several forms, materials, techniques and processes. These features, such as flying, defensive and offensive mechanisms and many others have inspired researchers, creative and enthusiasts into developing artificial solutions that mimic their natural counterparts. Early developments of biomimetic involved large structures, however, with current advances in mechanics, electronics, and computer science the development of micro and nano structures is allowing the creation of more complex, flexible and portable structures resembling biological features found in nature. These advances in robotics may help solve or improve tasks otherwise difficult with traditional robotics. This paper focuses on the design and development of soft-robotic manta ray prototype whose motion is controlled using magnetic fields over a body composed of a ferro-fluid. The goal is to explore magnetics actuation as an alternate mean to control and reduce soft-robotics size as an alternative to current traditional mechanical or electromechanical biomimetic developments and even shape memory alloys

1. Introduction

The evolution found in nature has provided sufficient material for analysis and research in the development of solutions in areas such as aerodynamics, self-cleaning, smart materials, self-assembly and energy conversion among many others, resulting in biologically inspired designs mimicking nature's functionality [1]. In the field of robotics several mechanisms have been inspired by the biomechanics of living animals, many of them with remarkable characteristics that human creations cannot meet yet.

Due to advances in micro mechanics, electronics and smart materials smaller components can be currently designed and fabricated, thus resulting in the miniaturization of robotics [2]. As the development of Micro Electro-Mechanical Material technologies increased many smart materials started being developed with applications as active, passive or wireless actuators. These smart materials used as actuators can be seen in a Shape Memory Alloy (SMA), Piezoelectric Actuators (PZT), Ionic Exchange Polymer Metal Composites (IPMC), and even ElectroMagnetic Actuators (EMA), among many others [3].

Soft-robotics is an emerging field of technology that is taking advantage of the properties from the advances in smart materials. Among the applications, smart materials can be used for developing miniature actuators that can resemble movements found in nature. [2]

Some of these smart materials are being used in several biomimetic inspired robots such as tadpoles, jellyfish, walking robots, fish and propelling fins as alternate locomotive actuators. Within these developments, advances has also been made in the development of manta ray-like micro robots actuated with SMA wires that can flexibly bend the fins [4]. One approach is a 3d swimming tadpole mini-robot that can move freely in water arranged with actuation mechanism of one permanent magnet powered wirelessly using an EMA system. [2] Other approaches in smart materials is the conduct polymer material developed as actuator, structural component and power deliver mechanism. [5] Emerged field of autonomous soft robotic fish powered by fluidic elastomer actuation system is also considered. [6] Or fish-like aquatic robotics using flexible bimorphs made of macro-fiber composite (MFC) piezoelectric laminates for carangiform locomotion. [7]

This paper explores the design and the development of a biomimetic inspired ferro-fluid controlled aquatic manta raysoft-robot. The manta ray is one of the most efficient fish swimmers (11.2 Km/h) considering its size, weight (up to 1300 kg) and morphology. Its unique motion characteristics allow saving more efficiently energy than any underwater vehicles created by human [8]. The main subject of study is their swimming modes based on propulsion or oscillation mode (fins lift up /down), which its uses in a cruise or long distance and high speed; and a second mode denominated undulation mode where energy is saved for swimming at low speeds, through an amplitude of motion at least the half of oscillation mode as presented in Figure 1. This navigational feature is the main topic of interest and research in robotics.

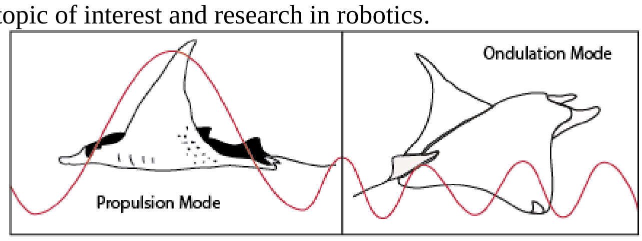

Figure 1. Manta ray’s swimming modes.

2. Materials and Methods

2.1. *Biomechanical and Mimetic Analysis*

The manta ray is characterized for its inaudibly swimming modes, low flapping frequency in slow speed and high flapping amplitude in long distance. It also has a highly manoeuvrability in vertical direction, horizontal direction and can instantly change course while swimming upwards and downwards. In addition, its unique stability and locomotion is caused by the position of its pectoral fins close to its centre of gravity [9].

The pectoral fins of the manta ray are characterized for their adaptation, efficiency and several numbers of achievable degrees of freedom due to its skeletal structure that allows moving in both directions and make 360 degrees turns [8]. Its remarkable adaptation, control and power allow the manta ray to leap out of water and even glide as bird for a few milliseconds.

During locomotion displacements the manta ray performs different movements within a single flap, these are important because the proximal and distal parts of the pectoral fin do different motions in any given moment. Also, the flexibility of the fins can be classified into two sections: the relatively rigid proximal part and the relatively flexible distal part. The proximal part is the first third part nearest to the body while the remaining part is distal part as presented in Figure 2 [9] [10].

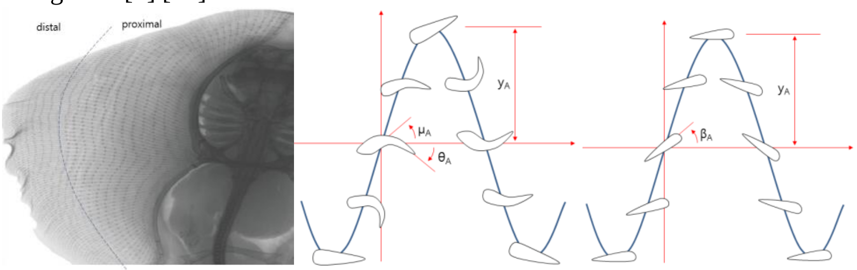

Figure 2. left: Manta ray's distal and proximal pectoral fin location; and simplified model of fin motions: center: front view, right: side view.[9].

2.2. *Design*

The manta swimming trajectory requires the movement of the pectoral fin in three dimensions for achieving both propulsion and undulation modes. The diagram model of its motion could be simplify in two ways, as presented from the frontal and side view as presented in Figure 2. A mechanical representation of the pectoral fin for exactly representing its movements would require a complex mathematical system composed of several linkages that would mimic the navigation modes. The fin deformation of Manta Ray requires mathematical model simplification with minimum degrees of freedom. [11]. This simplification is possible by locking the angular motion for simplicity, the model of proximal and distal parts will not consider; as a result, the angles μ_A, θ_A are not included, so the fin will act as a forehand flat surface described as follow:

$$y_A(t) = y.\sin(\omega t)$$
$$\beta_A(t) = \beta.\sin(\omega t + \varphi)$$

Where: β_A is the rotational angle, y_A is the maximum amplitude of translation displacement, ω is angular frequency and φ is phase difference.

2.3. *Passive Actuator: ferrofluid*

Considering that the goals is to develop a soft-robot, the ferro-fluid is chosen as it allows a stable colloidal suspension of sub-domain magnetic particles within a liquid carrier. The particles average size of about 100Å (10 nm) allows miniaturizing the robot's actuator. These particles are coated with a stabilizing dispersing agent (surfactant) which prevents their agglomeration even when a strong magnetic field gradient is applied [12]. Typically ferro-fluid contains in fraction of volume 5% magnetic solid, 10% surfactant and 85% carrier. The surfactant must overcome the attractive van der Waals and magnetic forces between the particles. In addition, surfactants have a polar head and non-polar tail (or vice versa). However, ferrofluids lose their magnetic properties at sufficiently high temperatures, known as the Curie temperature.

2.4. *Movement Control*

Soft robotics devices can mimic natural movements involving oscillations or undulations when the passive actuator is triggered through a magnetic field. The variations of amplitude and angle of deformations could be considered as a key factor resulting from the material's properties, such as the flexibility and the thickness that could be affected in the robot performance.

One common EMA system is a combination of 2D, 3D electromagnetic coils arranged at 90 degrees with one pair of Helmholtz, Maxwell, Uniform or Gradient coils which generates uniform magnetic field in x, y, z axes. As an example, these pair of coils generally consists of two identical circular magnetic coils, where the radius (r) of the coils is equal to the distance (d) between them for Helmholtz configuration. In addition, the applied currents in these coils flow in the same direction and have the same intensity in order to produce continuous magnetization. There are some other especial electromagnetic actuators designed to obtain similar results of magnetic field in all three axes with the advantage of increasing the region of interest (ROI).

In terms of the ferro-fluid material acting as an active actuator powered wirelessly by the magnetic field, can be expressed by the following equation:

$$F= \mu o V(M.\Delta)H$$

Where; μo is the magnetic permeability of free space, V is the volume of ferro-fluid particles, M is the magnetization of a ferrofluid, and the H is the magnetic field intensity applied [2]. The ferro-fluid responses when a magnetic field is applied, the magnetic particles placed in the soft-robot orient along the field lines almost instantly. The magnetization of the ferro-fluid responds immediately to the changes in the applied magnetic field and when the applied field is removed, the actuated areas back to original position.

In a gradient field the whole fluid responds as a homogeneous magnetic liquid which moves to the region of highest flux. This means that the ferro-fluid can be precisely positioned and controlled by an external magnetic field producing linear displacement acted in the soft robot. The forces holding the magnetic fluid in place are proportional to the gradient of the external field and the magnetization value of the fluid. This means that the retention force of a ferro-fluid can be adjusted by changing either the magnetization of the fluid or the magnetic field in the region or interest.

3. Experimental Results

Magnetic forces are been applied in all three axes as a preliminary test in order to produce horizontal motion and orientation on the manta ray with positive buoyance powered by the EMA system. The EMA system is composed of 1 Helmholtz coil and 1 Maxwell coil in x axis, 1 uniform coil in y axis, and 1 uniform coil and 1 gradient coil in z axis.

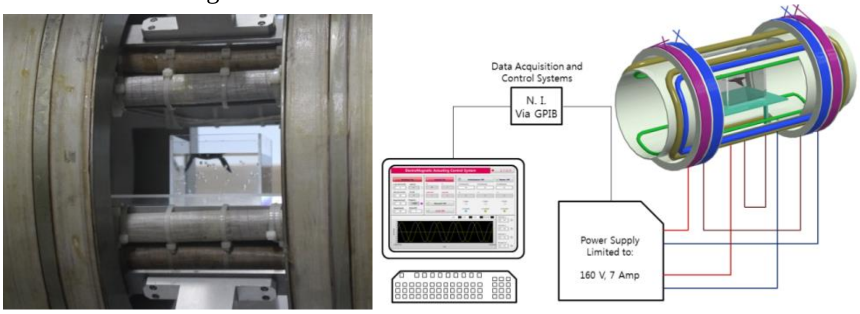

Figure 3. Left: Electro-magnetic actuation system; Right: Schematic diagram of EMA system power micro-robots.

Figure 3 (left) presents the electromagnetic actuator system used to execute the experiments with different robots shapes, however in this case the focus was on the manta ray. In the first trial the 5 cm robots were power only with z axes coils. The combinations of the two magnetic coils in the z-axis were controlled by a computer using Lab-view GUI and program via GPIB network protocol. The two coils were powered at 160 V dc with limited current of 7 Amp. The schematic diagram is showing in Figure 3 (right).

The process of constructing a soft-robot takes advantages from 3D printing of elastic polymers or even uses hands skills to assembly. The manta ray was constructed using flexible materials of thin film polymers. The biomimetic shape and scale is down into several times to achieve the model description. The pectoral fin and tail were made with 100 μm polyurethane film and 20 μm of polyethylene film sealed by a heat device which creating the contour shape of biomimetic robot, as presented in Figure 4.

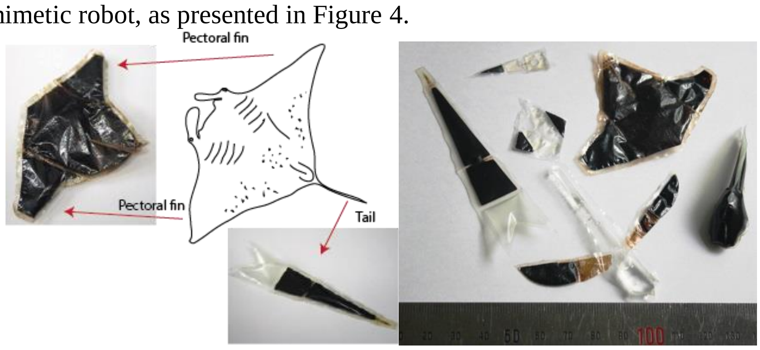

Figure 4. Left: soft robotic of manta ray like robot; right: different sizes of soft robotic prototypes.

The film materials are very flexible, thus allowing generating passively phase differences under the hydrodynamic force; furthermore they have a solid mechanical strength to recover back into its original shape. The motion is generated as a result of the induced magnetic field that allows changing the soft-robot form through the movement within the ferro-fluid.

Figure 5 presents the preliminary tests with 5 cm length prototypes exposed to the EMA system actuator. The picture allows visualizing a sequence of low frequency (2 Hz) magnetic field applied in the Z axis direction powered by the gradient coils. The sequences are showing a red line limit of maximum amplitudes reached by the robots when maximum positive voltages are applied. The voltages are sinusoidal oscillations in other to generate the undulations movements of the robot. In addition, similar performance is seen when negative values are applied. The reason of use half of sinusoidal voltages is due to the ferro-fluid does not have a positive of negative pole as a common magnet. So the returned forces to the original positions are done by the flexibility of the film. This result in high frequency voltage cannot be achieved in other to obtain better performances.

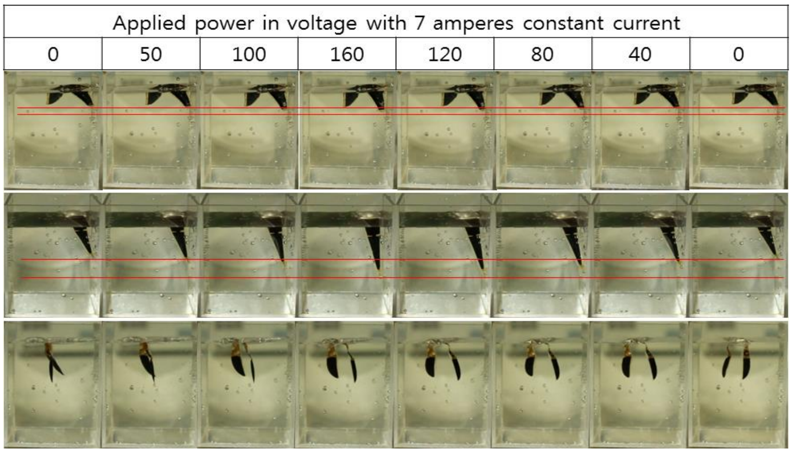

Figure 5. Biomimetic soft robot fin movement.

4. Discussion and Future Works

Several tests were performed with minimum success due to low effects of the actuator within the EMA system, as the ferro-fluid composition proved to required stronger magnetic fields to bend the fins; a possible solution is to use permanent magnets actuated by manual control or with high control theories involving for precise orientation and position.

After testing the manta ray it was observed that the performance and elasticity changed dramatically due to the evaporation of the ferro-fluid. This differences can be visually see between polyethylene film and polyurethane film, were last one keeps the ferrofluid for much longer as a liquid.

Ferro-fluids presented a remarkable actuation response in soft robots for future applications and improvements. However, to obtain a precise control it requires further analysis as nano particles for molecular motion. Also, the ferro-fluids could be considered as neutral monopole or magnetized dense liquid that follow the magnetic field with capillarity restrictions forces.

It is worth noting that during this exploration, ferro-fluids provided an interesting approach for the development of passive miniature actuators in the field of soft robotics, so the results of experimentation and applications could be consider as effort for further research.

Additional challenges arose from the tests, such as the difficulty to trace concentration material of ferro-particles in specific areas in order to improve the performance and also create a micro buoyancy space to execute in a flotation motions its horizontal displacements. So micro channels as alternative of powered the ferro-fluid is also possible in other to used its hydrodynamics properties.

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