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Ferrofluid Soft-robot Bio-inspired by Amoeba Locomotion

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Abstract: This paper presents a novel application based on the bio-inspired motion of the Amoeba. This research is focused on development a soft micro robot based on the Amoeba locomotion which can be named Whole Skin Locomotion. The robot is created using the fluid filled toroid method that acts as a body shaping feature with ferrofluid material placed within that is delivered to create the driving force. The passive fluid switch acts as an active sensitive liquid when a magnetic field is applied. Therefore, based on this behaviour in order to produce the driving motion external Electromagnetic coils are arranged as a wireless control and actuator. A number of motions and hindrances are currently presented to insure the principal motions of the robot. Some other approaches of ferrofluid soft-robot biomimetic inspired are also presented as well.

Keywords: Whole Skin Locomotion, Electromagnetic coils, Ferrofluid soft-robot.

1. INTRODUCTION

Several ways exist and exercises the behaviour of nature locomotion; some of them are the inspiration way of current micro-robots research like efficiency, pattern material and flexibility; where, in an intensive review and simulation of the trend of the movement result in a robot development increasingly improved.

Amoeba in one of most fascinated and efficiency ways of locomotion, due to its mobility based at the interior transported fluid of its body. Inspired by the cytoplasmic streaming motility mechanism of the single cell amoeba, the Whole Skin Locomotion mechanism WSL was proposed as an alternative locomotion strategy for mobile robots. [1, 3] It consist in elastic, silicone-skin toroid filled with water to demonstrate the feasibility of the WSL mechanism either with a solid tube inside (concentric solid tube model CST) filled with liquid or (fluid filled toroid model, FFT), or in the form of a novel tensegrity mechanism. [2]

On the other hand, researchers have studied on electromagnetic actuation method for micro-robots applications. Because, power source and actuator such electric motors could not be included in the micro-robots body locomotive; as a solutions micro size robots can be actuated by external magnetic field. Some micro-robot's locomotion uses the actuation by the electromagnetic field and several of them are bio-mimetically inspired with successful achievements; such as, swimming mini-robots tadpole and jellyfish robot. [4].

This paper presented a novel soft micro-robot of whole skin locomotion with ferrofluid material inside of fluid filled toroid (FFT) shape operating as passive and active actuator; which can have a potential development of miniaturization robot for medical applications like drug delivery system, intravascular catheters, gastronomic endoscopic, etc. The main advantages are that the WSL robot does not require any on-board driven system, rigid parts or actuators, easier to be manufacturing and greatest contact friction with the environment surface.

2. KINEMATIC ANALYSIS

At the same way of any wheel in a robot's movement, the WSL robot has its body's length as a traction and/or locomotion system. Considering that the Amoeba's motion is well performs in the micro and nano levels; the current development and studies is driven in the macro scale environment, most of the analysis would be more effective in similar conditions that the amoeba biologically acts and lives.

Currently, there are two motions focus in the micro robots research, one of them is the Euglena locomotion based in the oscillations of its body shape from back to front (tail to head) by changed its sizes. See Fig. 1. The second approach is based in the flagella motion, which is a lot more common in bacteria's locomotion like Salmonella Typhimurium; currently working (Fig. 1)

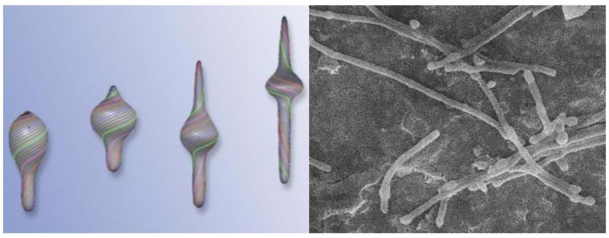

Fig. 1 Left: Euglena motion; Right: Salmonella Typhimurium.

The current research is emphasis in the Amoeba locomotion and its capabilities of moves by changing its body shape in a random way and even splitting and merged if a possible obstacle or target food is on the way. (See Fig. 2).

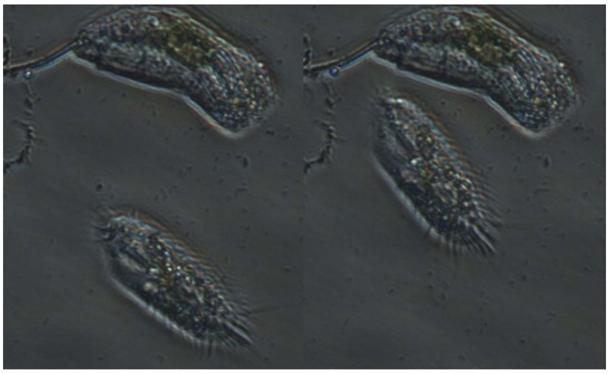

Fig. 2 Amoeba, under microscope

The amoeba is a jellylike mass of protoplasm (living matter) that is constantly changing its shape. A cell membrane encloses a thin outer layer of transparent protoplasm called the ectoplasm and a granular inner mass called the endoplasm. The endoplasm contains the cell nucleus, which controls the amoeba's life processes. (See figure 3) In most species, the endoplasm also contains a water bubble, called the contractile vacuole that regulates the amoeba's water content. Within the endoplasm there are also bits of food enclosed in food vacuoles. [5, 6]

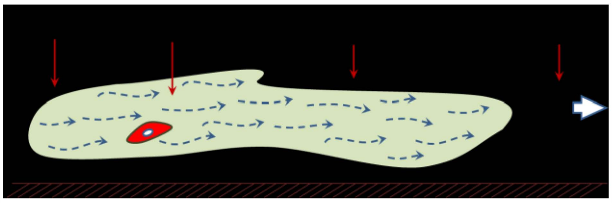

Fig. 3 Schematic graph of Amoeba locomotion

The amoeba does not have permanent body parts to perform its various functions; it uses temporary extensions of its body to move from place to place and to capture food. These temporary extensions are called pseudopodia. Its pseudopods come from the Greek words for “false” and “foot”, these are flowing projections of cytoplasm that extend and pull the amoeba forward or engulf food particles, a process called cytoplasmic streaming. [6] The amoeba's food includes other protozoans, rotifers, and microscopic algae and roundworms. It obtains these organisms by extending pseudopodia to surround them; the organisms are then digested within the food vacuoles. [5, 6] (See Fig. 2, 3)

3. ROBOT DESIGN AND ELECTROMAGNETIC ACTUATION

3.1 Micro robot design

The process of constructing any soft robot takes advantages of 3D printing technology with elastic polymers, powder materials and UV spouse reacting or even hands skills to assembly. The WSL robot has been built after several trials due to its 3D shape and small size in hand skill performances. It uses a flexible thin film polymer of 20 μm polyethylene film and closing its outline shape by industrial glue.

The way of the WSL robot produce its mechanical motion force is based in the friction contact with the surface and the electromagnetic force applied in the ferro-fluid. When magnetic field is applying at some distance a head of the robot the ferrofluid acts as actuator by rotating its skin body on its own spot. As a result, the robot moves forward or backward in straight line. In addition, when the film reaches its limit point, it returns to back by its middle body area, therefore, the WSL robot becomes as loop cycle itself. (See Fig. 4).

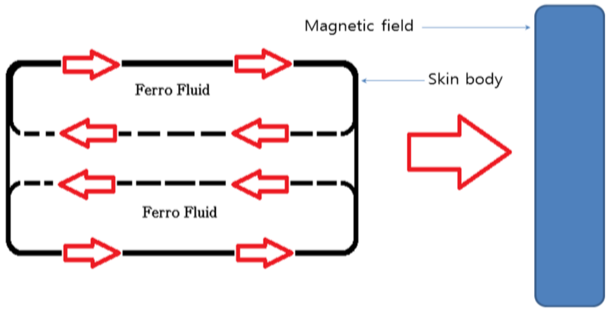

Fig. 4 Schematic mechanism of WSL robot

3.2 Ferro-fluid Actuator

Ferrofluid is based of iron particles in the nano-scale mixed in oil water which both act as a none-polar liquid. The fluid is very sensitive material when come across to magnetic fields, it can changes in various forms along the magnetic field lines. (See Fig. 5-left)

Fig. 5 Left: Ferro-fluid shapes affected by magnetic field lines; Right: Body shape of WSL robot

Ferro-fluid 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 [7]. 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). But, ferrofluid loses its magnetic properties at sufficiently high temperatures that known the Curie temperature [8].

3.3 Electromagnetic Actuation (EMA) System

Micro and nano robotics are a recent example of MEMS technology based in the fabrication of wireless magnetic robot powered by an electromagnetic coils at a specific arrange. 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 of the coils is equal to the distance between them for Helmholtz configuration [9]. In addition, the applied currents in these coils flow in the same direction and have the same intensity in order to produce continuous magnetization. [10]

There are some other especial EMA systems designed to obtain similar results of magnetic field in all three axes with the advantage of increasing the region of interest (ROI) like saddle coils type [12] and by increasing the magnetic field in the ROI like Octo-mag. [11]

In terms of the ferro-fluid material when is acting as an active actuator powered by the wirelessly EMA, 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 [12]. The ferro-fluid responses when a magnetic field is applied, the magnetic particles placed in the soft-robot oriented along the field lines almost instantly. The magnetization of the ferro-fluid responds immediately in the WSL robot by changing its body position targeting the applied magnetic field; in contracts, when the applied field is removed the WSL robot stops. (See Fig. 6)

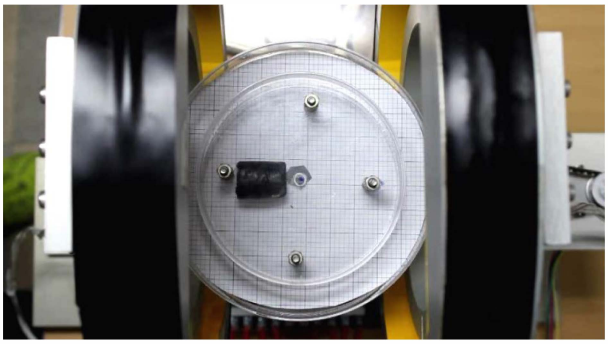

Fig. 6 Electromagnetic actuation system for WSL robot

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 the external magnetic field producing linear displacement acted in the 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.

4. EXPERIMENTAL RESULTS

To perform the experiments a number of pairs of coils acting as wireless actuators were required to produce the motion of WSL robot; these are called Helmholtz coils and Maxwell coils depending of the applications. The preliminary test was set by power the Helmholtz coils to produce the orientation angle of the robot along the X axis, and them, to produce the horizontal displacement of the WSL robot along the axis of the coils were powered only the Maxwell coils; but also both pair of coils can be activated if more electromagnetic field (force) is required. In additions, by changing the direction of the current in the coils, the robot can move forward or backward along the axis. (See Fig. 7)

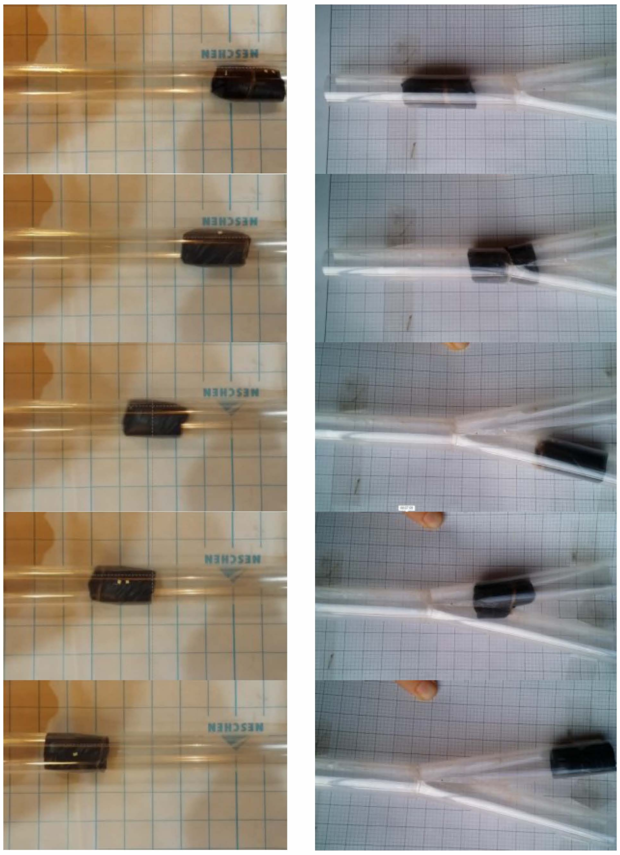

Fig. 7 Left: First trials along X axis of WSL robot; Right: Steering motion of WSL robot

The second experiment required four pairs of coils two Helmholtz and two Maxwell placed at 90 degree acting like X, Y axis of electromagnetic field. The Fig. 7 (left) is showing a sequences of pictures as a result of motion performance by the WSL robot along the X axis, which is clearly see that the 20 μm polyethylene film glued as toroid shape and filled with ferro-fluid can achieve a smooth motion and also could have potential applications in the soft robotics technology; in additions, others tested were executed in a second mock-up pipeline with Y junction, which the results are the steered motion of the robot; these can be also seen in the sequences pictures of Fig. 7 (right).

A brief conclusion of these experiments prove that the WSL robot can perform inwards straight motion in a pipeline when X axis electromagnetic field is applied and also it can makes left and right directions when X and Y axis of the EMA coils are powered producing motion and orientation in a desired path trajectory.

The further experiment was to place the WSL robot in a double flat surface with 15 mm air gab to calculate the behavior of steered motion. Two axes of electromagnetic actuator were set-up and one vision system was used to extract the numerical data from (Vegas) computer software. The calculated values were position, velocity and accelerations of the WSL robot in the setting mock-up. The current applied in the electromagnetic coils were 7.5 amps at 150 V.

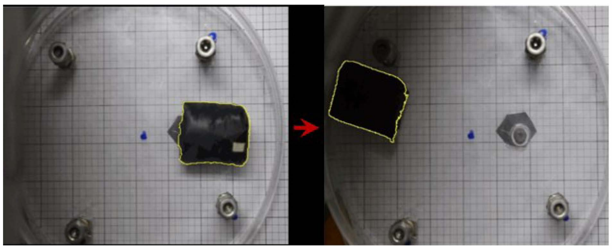

Fig. 8 Left: Position set as a reference point; Right: Final orientation and position of WSL robot after motion.

Fig. 8 (left) is showing the first position (0, 0) setup as reference point before the motion begins. The right picture of figure 8 is showing the final relative position of WSL robot with a result of (-52.686, 11.504), tweeted tangent angle of 156.588; both values were extracted from Vegas software.

Basic calculations can be done from the data, like the radius of curvature generated by the robot was 126.4 mm and also velocity and acceleration with a displacement time of about 3 seconds.

Considering that the project has achieved a novel application with ferro-fluid for soft-robotics there are some hindrances that hope some other research can be improve; one of them is the hand skills required to fabricated the FFT body shape affecting by none constant smooth motion when the sealed area is in contact with the surface, generated unstable motion and speed, which nearly impossible to control by EMA system. This because, when the sealed area get-out from the middle point of the WSL robot is necessarily to apply high magnetic field in order to break the tangential forces of the film, which are acting in an opposite direction. In addition, when the sealed area is going over, the high applied magnetic field makes the robot speed-up and even jump out from the EMA system.

Some others difficulties were to filled the ferro-fluid into the FFT shape, for doing so, the fluid is injected with a tinny needle, but the inner hole has to be close by the glue, created another distortion in the body shape follow-on of smooth locomotion. Therefore, based on these conditions different sealed methods and others biomimetic approaches derived based on these with ferrofluid material as actuator for micro robots, some of them are presented next.

5. OTHER APPROACHES WITH FERRO-FLUID ACTUATIONS AS SOFT-ROBOT

Fig. 9 shows some others approaches considering by basic principles of hydrodynamics, where film materials stiffness and flexibility allowing generate passively phase differences under the hydrodynamic force; furthermore they have a solid mechanical strength to recover back into its original shape. The motions generated as a result of the induced magnetic field that allows changing the soft-robot form through the movement within the ferro-fluid. [13, 14, 15]

The strategy been done is from a 2D shape polyethylene film and as a replace of glue the shape of robots are created by a thermoplastic sealed device. It has the advantage of recreated a different flat straight shapes with concentrated areas of ferro-fluid and also empty areas acting as buoyance tanks.

Fig. 9 Various soft robot with different approaches and shapes using ferro-fluid

Fig. 10 presents a sequence of 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. As a result it is only necessarily half of sinusoidal voltage due to the ferro-fluid does not have a positive of negative poles as a common magnet. So the returned forces to the original positions are done by the flexibility of the film. These also result that in high frequency voltage cannot be achieved in other to obtain better performances; nevertheless, potential applications can be achieved in a near research future and enhances.

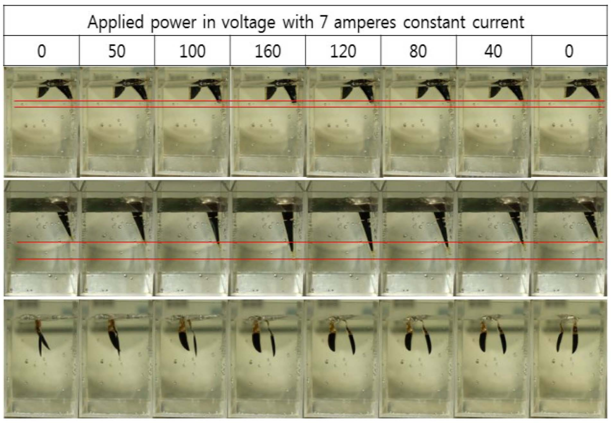

Fig. 10 Preliminary actuation tests of others biomimetic soft robots

6. CONCLUSIONS

Using the movement of one single cell like amoeba animals move implemented as a biomimetic soft robotic and using a Ferrofluid as passive/active actuator, the movement of this new approaches' method of whole skin locomotion motility is confirmed through various experiments is a step forward for future applications. Fluid-filled toroid in the human digestion system is a potential application for drug delivery system or if possible further miniaturization movement in the vessel is also expected to be achieved through the control of an external magnetic field in intravascular applications. As a main advantage of the WSL robot proved that is possible to achieve the two-dimensional movement and not a simple linear motion. Where, ferro-fluids can offer 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.

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 a flotation motions its horizontal displacements for the underwater applications. However, micro channels as alternative of powered the ferro-fluid is also possible in other to used its hydrodynamics properties.

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