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Micro-embedded Skimmer in Autonomous Underwater Micro-robots

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Abstract: Bio-inspired underwater micro-robots with inspire from dynamic variant spaces of animals utilizing of the ICPF (Ionic Conducting Polymer Films) actuator as a propulsion is developed recently. These micro-robots with multi Degrees of Freedom cause them walk smoothly in underwater environments have urgently been demanded with variety kinds of application such as medical, detection, and industry. In this micro-robot with inspire from the motional mechanism by ICPF actuators of an inchworm motion for grasping to the OOZE, and also the movement mechanism of jellyfish for sampling from the surface of the water in limited places according to the difference of the density of the water are used at the moment. We calculated and simulated the mechanism and walking speed of the micro-robot. A preliminary pattern was designed and also a collection of the research for appraisal the locomotion and the floating speed motion were done in detail. Employing ICPF as micro actuators to fabricate a four-finger gripper and six micro actuators were used to implement grasping.

Keywords: Bio-Inspired Underwater Micro-Robot, Inchworm & Jellyfish, Micro-Mechanism, Micro Actuators, Ionic Conducting Polymer Film (ICPF), Skimmer, Hydrodynamic Modeling

1. Introduction

In this paper proposed the design of novel micro-robot based on the motion of an inchworm and a jellyfish. Bio-inspired underwater micro-robots with multiple Degrees of Freedom (DOF) that can walk and swim smoothly in water environment media are of great interest for underwater monitoring operations including monitoring ocean currents, medical robotics, depth measurements, studying animal migration and underwater environments exploration in the future [1-3].The capability of locomotion is the most important aspect of micro- robots to accomplish on-board control and given tasks. In regard to the mini actuators, they play a key role and effective in the micro-robot systems. Endoskeleton structures living organisms have been inspired for building miniature scale robots in the field of robotics.

Many reported micro-robots are driven by various kinds of, such as Ion-exchange Membrane Metal Composites (IEMMC) or Piezoelectric Elements (PZT), electromagnetic actuators, electrostatic actuators, stepper motors, pneumatic actuators, and Shape Memory Alloy (SMA) were developed to use as artificial muscles in novel types of micro-swimming robots [4-6]. ICPF (Ionic Conducting Polymer Film) actuators are made of film composite Perfluoro Sulfonic acid (PFS) polymer plated on its and surface platinum layers (one side is 0.003mm in thickness). Micro ICPF actuators are very active micro actuators that show highly large deformation in the attendance of low practical voltage and low impedance. ICPF is becoming one of the most exciting continuous research district in Bio-MEMS, and is paving the way to a major diversity of biomimetic nigh for underwater micro-swimming robots design [7-10]. An inchworm motions forward by two periodic kinds of stroke locomotion. The first one is longitudinal traction locomotion and the second one is Omega (Ω) shape constantly bending locomotion [11] as shown in Fig. 1.

Though many of bio-inspired underwater micro-robots agitate by smart micro actuators and materials have been developed in recent years, unfortunately these traits repugnance with each other. The application of ICPF actuators are in developing the micro-robots with a compact structure, flexibility and multi-functionality by low voltage

[12]. When the voltage is served on its surfaces, it bends into anode side. The displacement of the micro ICPF actuators are commensurate to the current intensity which applied on it. The other characteristics of the ICPF actuators are when the frequency of the applied current intensity is lower than 0.3Hz, the water around the micro ICPF surface actuators are electrolyzed [13]. In recent studies, various underwater micro- robots utilize ICPF have been developed, including one by Tadokoro et al that an actuator model of ICPF for robotic applications on the basis of physicochemical hypotheses [14]. Yunchun Yang et al proposed a new prototype model of jellyfish-like micro-robot utilizing SMA and ICPF actuators [15]. An inchworm underwater micro-robot with use of the locomotion under the water by changing the volume continuous function of micro ICPF actuators and by electrolyzing the water to do floating motions on the surface of water for sampling from the organic small structures of the surface the water by utilizing the skimmer and the locomotion mechanism which was inspired by the jellyfish. In this research two types of locomotion pattern and mechanism of inchworm, jellyfish and butterfly were inspired in order to implement more functions, improving and speeding the move of micro-robot that is developed with ten micro ICPF actuators utilized as legs .This unit employed four of its micro actuators as floating, walking, and rotating motions. The other six micro actuators were employed to implement grasping.

And the rest of paper is organized as follows:

Section 2 proposed multi-functional locomotion based on 1-DOF and 2-DOF. A novel type of underwater, using ICPF actuators as legs or fingers that can do floating, walking, rotating, and grasping motions were clearly introduced. In floating motion the water around the surfaces of the ICPF actuators was electrolyzed by decreasing the frequency of the applied voltage to 0.4 Hz.

Section 3, the skimmer is designed, since the organic samples are made in limited .D.B.O.S system by using the difference of the density of the water and the organic sample in any moment make it possible to collocate the sample from the organic species and transfer samples to the laboratory. At the moment this micro-robot is the first vehicle with small structures scale beside, sampling from the surface of the water in impenetrable places and generally non-traffic places, has the ability of moving underwater, on the other hand it clears the water of the different places. D.B.O.S system causes the passes of the water from the surface section, and some advantages are presented. And finally our conclusion.

Table 1. *The list of abbreviations*

IPMC	Ionic Polymer Metal Composite
ICPF	Ionic Conducting Polymer Film
SMA	Shape Memory Alloy
DC	Direct Current
DOF	Degrees Of Freedom
SSC	Smart Soft Composite
DBOS	Density Base Organic Structure

Fig. 1. *Locomotion pattern of an inchworm. Crawling motion (Omega motion)*

2. Proposed Multi-Functional Underwater

2.1. Proposed Underwater Micro-Robot Structure

A novel and application biomimetic structure with ten ICPF actuators were considered in this work. With regard to combined inchworm-jellyfish, and the structure of skimmer, our design would be limited. For instance, the proposed skimmer only sample on the surface of water, so lying mode was selected. Inchworm also can do only walking motion. Hence, two types of motion is necessary. The first one is standing mode, and the second one is lying mode.

In order to understand these two motions the following figure along with the order of ICPF actuators was introduced. It is very simple yet more efficient especially in limited places and obstacle avoidance.

Since the micro-robot should be multifunctional locomotion, simple ICPF actuators play a significant role in this research. In regard to these actuators (legs or fingers) robot could move in longitudinal and transverse directions, do grasping and floating motions, lying and standing structures, swimming, walking in the air, and also walking in a flat surface. These locomotion indicate that the micro-robot is multifunctional locomotion.

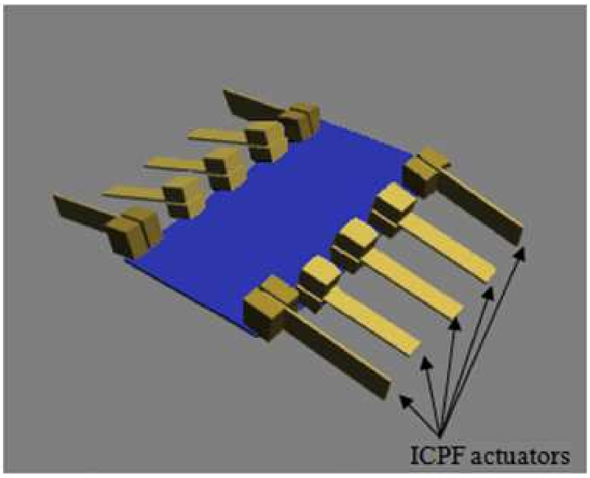

Fig. 2. *Proposed biomimetic Micro-robot structure*

As illustrated in Figs 2, 7 legs are numbered I to IV rather than other actuators have 90˚ phase difference. The reason for the 90˚ phase difference can be for longitudinal and transverse directions based on its locomotion. More detailed information is clarified in the relevant section. It can be inferred that actuators I through IV as the legs which have a significant role in its locomotion. They can be used as the following legs or the leading legs.

2.2. Structure and Driving Mechanism of Inchworm & Jellyfish

This paper describes and analysis of the design based on the motion of ascotis selenaria. To mimic locomotion patterns of the inchworm's behavior in nature, we observed what motions could be made by Ascotis Selenaria and chose motions as shown in Fig. 1.

Ascotis selenaria is a species of inchworm with a locomotion pattern similar an omega in bending motion especially between the extension motions. This species of inchworm can journey approximately its body length per move on a ragged surfaces, climb of leaf edges and branches of trees.

The particular species Aurelia aurita is often called "moon jelly," after its milky, translucent color and shape. The term "jellyfish" also refers to its gelatinous body. However, A. aurita is obviously not made of jelly nor a fish species, but instead a free-flowing creature that is able to propel itself though the water with muscular contraction of its bell [16].Fig.3 clarified the structure of different parts of the its body.

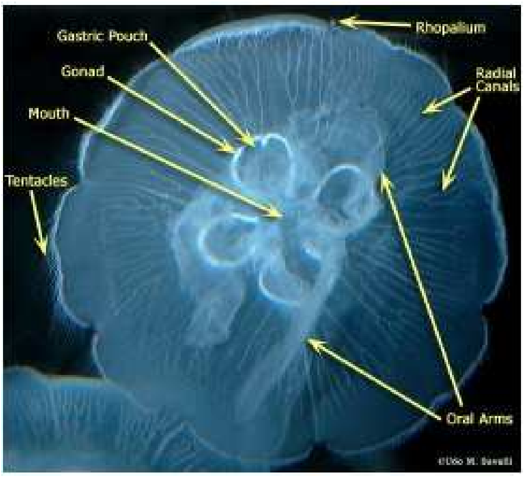

Fig. 3. *Schematics structure of the body jellyfish.*

2.3. Mechanism of the Walking Motion

In previous researches, the walking mechanism of inchworm with one and two DOF were investigated. It is evident that ICPF actuators make the proposed micro-robot move to the four directions. As can be seen clearly, these legs were the sequence parallel to the length.

We will face problem in order to walk in both East and West directions. Fig.4 clarified that four legs have different phase. Therefore, without adding another 4 actuators, this problem was creatively solved.

To understand better the walking mechanism, the following and leading legs were introduced. Note that the proposed micro-robot could move to the four directions. In this section two directions would be described. Hence, Based on the situation one leg was known as the leading leg, and the other was known as the following leg. Now, if the robot is walking in transverse direction, the leading and following legs will be like in Fig.4, otherwise the leading and following legs would change so as to get to the longitudinal direction.

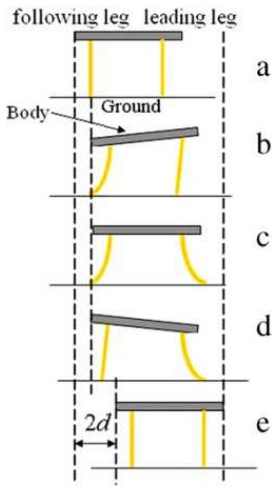

Fig. 4. *Micro-robot crawling mechanism*

In order to simulate the speed of walking motion of the proposed robot, the displacement of the drivers and the input frequency were considered. Note that the displacement of the actuator in an actual application is demonstrated by d the actuator, and also the displacement of the actuator without payload is demonstrated by d_0. Regarding the water resistance, potential damping, vortex shedding damping, viscosity, payload, and other factors, the displacement of the drivers decrease by a non-negligible amount 1d. Hence, the relationship between d_0 and d and the walking speed of the micro-robot are as follows [17]:

$$d = d_0 - \Delta d \quad (1)$$

$$v=2(d_0 - \Delta d)f \quad (2)$$

Where v the average speed and f is is the frequency of the input signal.

Note that the average speed is based on the input frequency from the average of experimental results or simulation results.

2.3.1. Walking Speed in the Air

Legs V through X were used to move in transverse direction and legs I through IV were used in order to move in longitudinal direction (see Fig. 5).Now, if transverse direction was selected, legs II, III were used as leading legs and legs I,III as following legs ,while in longitudinal direction legs order would change.

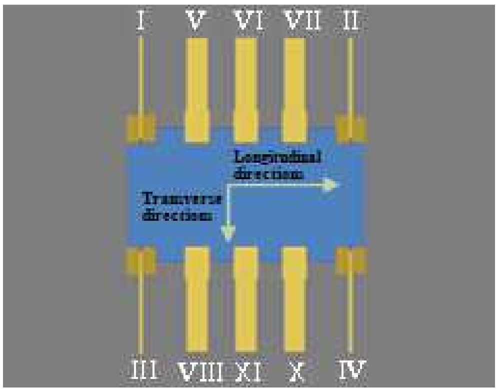

Fig. 5. *Top view Sequence of ten legs of the micro-robot. (In lying mode)*

Based on longitudinal and transverse directions, it can be clarified that ICPF actuators I through IV have a significant role in the proposed robot in this work. In order to simulate the walking speed one of longitudinal or transverse directions must be chosen to have the highest efficiency. Hence, two directions were simulated, and the graph of the two simulations were 100% fit (by using command Correlation MATLAB). This simulation result clarified that two direction could be chosen and the efficiency of them will be equal. It is worth noting that the whole frequency of legs must be the same. If the frequencies are not equal, the micro-robot won't mimic bio-inspired motion or maybe lose its equilibrium. As can be seen in Fig.6, ten frequencies is chosen to evaluate its performance in different conditions.

The simulation results are shown in Fig.6. It can be inferred as follows:

1. At 7V, maximum of walking speed 0.90 mm/s was achieve at 0.75 Hz.
2. At 4V, maximum of walking speed 0.50 mm/s was achieved at 0.75 Hz.
3. Before 0.75 Hz walking speed in air increased quickly, and after 0.75 Hz walking speed in air quickly reduced, therefore the value become zero within 2.83 to 5 Hz.

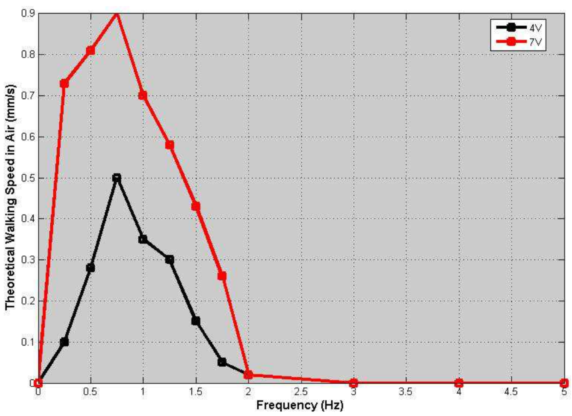

Fig. 6. *Theoretical walking speed results in air.*

2.3.2. Grasping and Floating Simulations With and Without Payloads

The main purpose of developing underwater micro-robots is to enable monitoring operations, such as video mapping in limited places or in unstructured underwater environments, and itself must carry the sample (object). Hence this section called " Grasping and floating experiments with and without payloads". So, in order to attain the main purpose of this research first grasping, and then floating with payloads were considered. Biomimetic of combined inchworm and Jellyfish in just one micro-robot was introduced without any contradiction, although it was a hard job. Section 2.6 clarifies the grasping motion in detail.

The simulation results of floating speeds with and without payloads (MATLAB 2014b) can be seen in Fig.7. From the simulation results, it can be inferred that:

1- The micro-robot could carry 0.5g, and maximum floating speed 4.33 mm/s was attained.

2- The micro-robot could carry up to 0.6g, and floating speed reduces to exactly 0.98 mm/s.

3- When the biomimetic micro-robot is without payload (0 g), as it can be expected, the proposed robot will have maximum floating speed 7 mm/s. it clarifies that the micro-robot has maximum floating speed than 0.5g, 0.6g, and 0.7g. This section along the previous section were clarified the multi-functional locomotion of the proposed micro-robot based on inchworm-jellyfish inspiration.

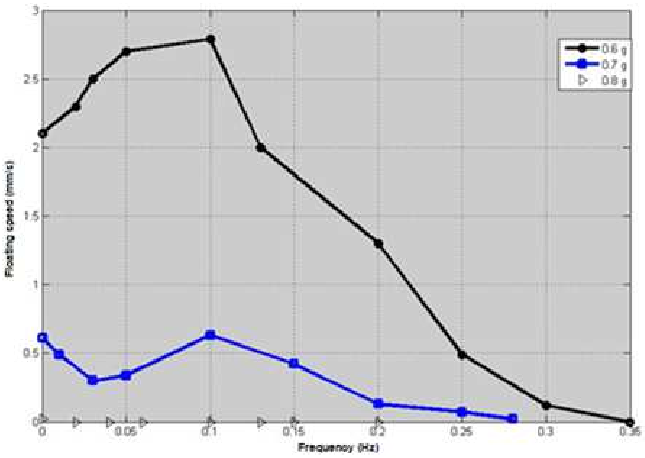

Fig. 7. *Experimental floating speed results with payloads (7V)*

2.4. Mechanism of the Rotating Motion

As can be seen in Fig.5 the two legs I and IV were used as following legs and legs II, and III were used as leading legs, this simple movement make the micro-robot easily to rotate clockwise. Now, if the leading and the following legs were change, the counter-clockwise rotation will be considered. The speed of the rotating motion could be simply calculated by the rotational angle covered in a single cycle along with the frequency of the pace.

The displacement of a single ICPF actuator by applying different signals was carefully calculated in order to simulate the theoretical walking and crawling speeds of the robot.

It can be seen clearly the theoretical displacements d_0, without payload, of the actuator in Fig.8. The simulation results of the theoretical walking speed could be clearly seen in Fig 9. From the simulation results, it can be inferred that if the frequency increases, the displacements of ten actuators increases. So, this is a good sign because the proposed micro-robot has the maximum walking speed. If the response from the displacements of actuators don't last, it will help us to develop a faster biomimetic micro-robot in future, since response is too important in micro-robots, and also in Nano-robots.

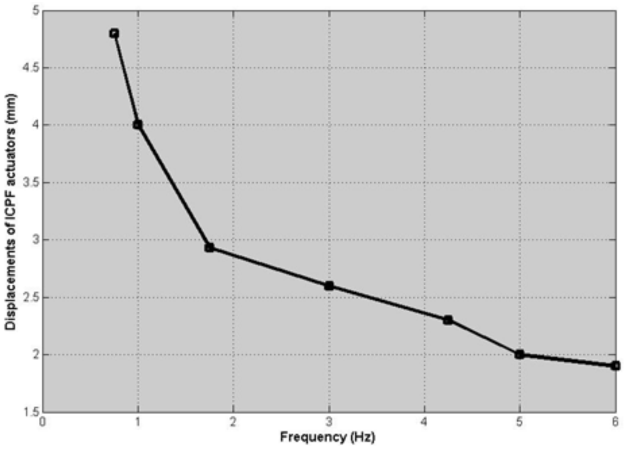

Fig. 8. Displacement (d_0) of the ICPF actuator (7 V).

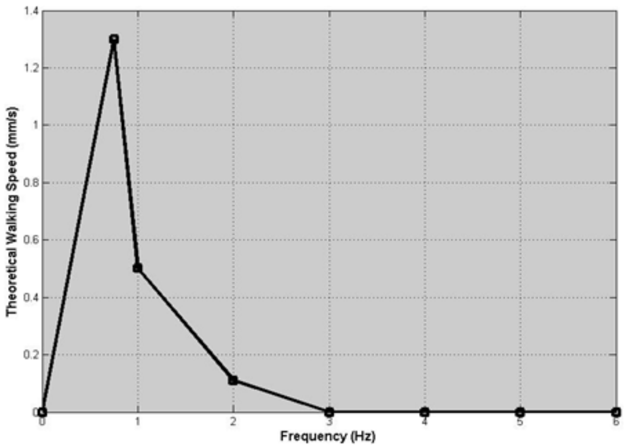

Fig. 9.Theoretical walking speed of the micro-robot (7V).

2.5. Mechanism of the Floating Motion

As can be obviously seen in table 2, buoyancy force compared with mg. Buoyancy is an upward force exerted by a fluid that opposes the weight of an immersed object. Thus a column of fluid, or an object submerged in the fluid, experiences greater pressure at the bottom of the column than at the top. This difference in pressure results in a net force which inclines in order to accelerate an object upwards. The magnitude of that force is proportional to the difference in the pressure between the top and the bottom of the column, and is also equivalent to the weight of the fluid that would otherwise occupy the column, i.e. the displaced fluid. For this reason, an object whose density is higher than that of the fluid by which it is submerged tends in order to sink. If the object is either less dense than the liquid or is shaped correctly, the force can keep the object floating. This can just happen in a reference frame which either has a gravitational field or is accelerating because of a force other than gravity defining a "downward" direction (that is, a non-inertial reference frame). Note that the center of buoyancy of an object is the centroid of the displaced volume of fluid. It is worth noting that buoyancy force is independent of shape. The buoyancy force is as follows [15, 17]:

$$F_b=\rho g(v+\Delta v) \quad (3)$$

where ρ is the density of water, g is the acceleration due to gravity and supposed to be 9.806 , V is the volume of the micro-robot, ΔV is the volume of the bubbles. Remember that the volume of the bubbles usually considered to be zero in the calculations. It can be inferred that floating motion is one of the most important section in this research.

Though motions such as, floating, walking, standing, lying are simple but too important since the combination of these simple movements could be, like sections 2.3.1 and 2.3.2, used in different situations in order to achieve our purpose.

Table 2.*buoyancy force in robot*

$F_b > mg$	floating upward
$F_b = mg$	suspended
$F_b < mg$	Sinking downward

The Buoyancy force was functioned in MATLAB since it is an important force which will be used in future. The Mfile of buoyancy force is presented in appendix 1.

2.6. Mechanism of the Grasping Motion

Based on the object where located, ICPF actuators or were used in this mechanism in order to grasp the desired object. Now, the robot could do two locomotion based on its situation as follows:

1-like the actions that explained in section 2.3.2

2-Carrying the object itself to the desired place. Remember that Number 2 was used while the proposed robot which is located in limited place or surrounded by obstacles, etc. In order to achieve this purpose, the micro-robot could change its place with ten ICPF actuators, and about obstacles (by using obstacle avoidance) bypass the obstacles. Finally the micro-robot (with payloads) can do floating motion.

Leg pairs V–VIII, VI–IX , and VII–X bent toward each other in order to grasp tightly the object and get to desire place.

3. Density Base Organic Structure (D.B.O.S)

3.1. The Structure of D.B.O.S.

In fact all organic samples are made in limited places. So, this system is called skimmer and is designed in a way that micro-robot be installable.

After transferring, the skimmer system is located to the sampling place by micro-robot in the function of sampling and when the water including of the sample leaded to it, the action of self-sampling and water (because of the density of the water is more than the sample) is done and will provide the following advantages such as:

A. At the moment this micro-robot is the first vehicle with small structures scale beside, sampling from the surface of the water in inaccessible places and generally non-traffic places, has the ability of moving underwater, on the other hand it clears the water of the different places D.B.O.S system causes the passes of the water from the surface section. So it leads to the descend of the stream of the water and it has significant function with a high intense in the way of the river.

B. As the result of the existence of different pathogenic micro-organism and their variety in the sample and in the place of sampling, sampling without facilities and doing it in traditional way increases the possibility of the disease. It is the most functional, inexpensive, fastest and easiest possible way of using this micro-robot in sampling and in the view of the health problem it exclusively causes the descend of the pollution and finally it is transferred. Although there are different traditional ways for sampling but because of wasting a long period of time and their expenses, bearing their exclusive expenses and vitally the cause of disease in the sampling made it impossible.

D.B.O.S system which uses the difference of the density of the water and the organic sample in any moment make it easy possible to collocate the sample from the organic species. So, because of protecting the sample in installed micro-tube which is located under the tanker make it possible for the transmutative samples lead to the laboratory .Fig. 10 clarifies structure of the D.B.O.S system.

Performance the process of detachment is according to the difference of the dense of the middle of the water and the organic samples while the stream of the water with the sample is lead into the system while entering it passes from diagonal page having a lot of holes.

This page with axial frame is connected and in spite of that water full of the sample avoided its stream, causes forward slow motion and lead to the navigations of four departed channel. This channel is installed in order to prevent it from rotational and abysmal stream the slow motion section of the water located in the down part, exit from the adjustable locating in the floor of the system and the collection of the sampler are lead to the final tanker. The height of the wall in tanker ,that is adjustable according to the density of the sample, make it possible to collection the maximum sample such as organic materials and biological species. At last the collection of the samples are transferred to the micro-tube using under the tanker (see Fig. 11)

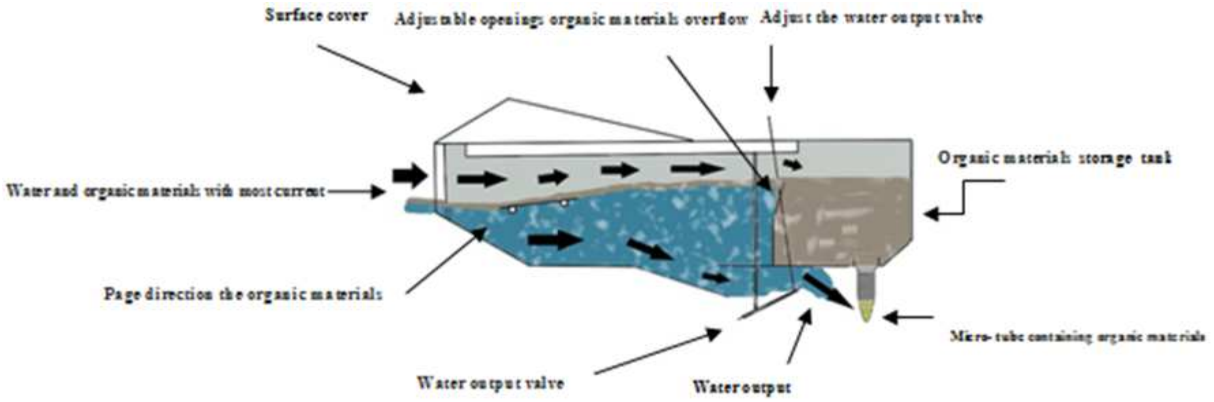

Fig. 10. *Density Base Organic materials Skimmer D.B.O.S*

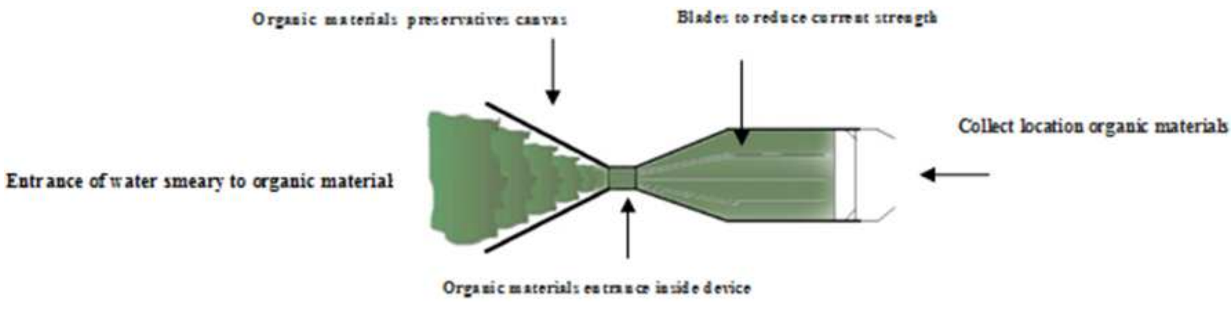

Fig. 11. *Top view of the separation of oil and water based density Skimmer D.B.O.S.*

3.2. Electro-Magnetic Valve

In this section, our aim is to open or close the cap of the proposed skimmer in every moment. Contactor consists of an electric magnet which has a rotational section, and a fix part of separate or connected by a single spring. Note that the contactor connected to the rotational part of a series of contacts are insulated with that rotate.

When the magnetic coil passes through a certain flow moving contacts by the magnetic force of the fixed contacts are pressed at the same time one or more springs are compressed or stretched. However when the voltage is interrupted or below a certain limit. Spring forces causes the contacts automatically separated.

Fig. 12. *Prototype of an Electro-Magnetic valve*

4. Conclusion and Future Works

In the proposed paper, a new species of the micro-robot including two groups of motional inchworm and jellyfish with small structures, multi-functional and flexible structures by using ten ICPF actuators were introduced.

Four actuators of inchworm micro-robot is used as the foot for swirling , walking , and floating motions and the rest of actuators are used in order to implement grasping motion. We calculated and analyzed the function of embedded skimmer to the foot and the speed of walking theoretically. In spite of the ability in biomimetic the inchworm motions, has the ability of doing the floating motions in the order of the sampling of the organic structures of the surface of the water .This clearly shows the wide range of the application of ICPF actuators in using biomimetic locomotion of marine organisms in micro-robots with changes of the volume and continuous function of ICPF actuators and by electrolyzing the water around the surface of actuators which causes the proposed micro-robot to do floating motions.

A unique feature of the proposed paper if compared with past papers could be used skimmer (for the first time) in order to increase the speed and improve the design by using the density of water and the possibility of collecting samples of the biological species in every moment. The reservoir is designed so as to preserve the proposed sample, and this makes the possibility of quick and easy transfer of samples to the laboratory environment extraction make so easy.

As the future work in this field, the mechanical structure and also the navigation will be designed to be intelligent. In order to aim this, meta-heuristic methods such as genetic algorithm are very helpful [21-23]. To evaluate the performance of mechanical structure design in different environments modeling of a robot navigation environment ,and then make some different scenarios in order to estimate the performance of mechanical structure. Given that the study of mechanical and structure properties in different environment require intelligent methods the genetic algorithms could be used to get the best structure which depending on the characteristics of the different navigation. To check the routing path according to the characteristics of the design robot, the processor could be programmed by using meta-heuristic methods to improve its performance.

The other features could be used to simulate the biomimetic of both inchworm and jellyfish in just one micro-robot without any contradiction, although it was a hard job.

But, there are still some obstacles and problems which must be studied in the future as follows:

1. Studying about grasping of the objects.
2. Improving the speed of the proposed micro-robot.
3. Using the materials which can effectively mimic jellyfish movement except micro IPMC and ICPF actuators.
4. Designing a novel micro-robot with this size or smaller than the amount offered for more depth.

Acknowledgments

The authors would acknowledge the work of all those who contributed to earlier versions of the paper Shuxiang Guo, Maoxun Li, Liwei Shi, Shilian Mao.

Appendix

```
function  [condition]=floating
format short;
dbclear all;  %clear all breakpoints.
disp(license);     % returns the license number for this MATLAB® product.
disp(pwd);         % displays the MATLAB® current folder.
disp(computer);  % Information about computer on which MATLAB® software is running.
display('---------------------------------------------');
tic;
%
%
g=9.806;
Density_water=input('Enter the density of your experiment= ');
deltav=0;   %usually considered to be zero in the calculations.
m=input('Enter the mass of robot (kg)= ');
disp('  ');  %Insert a blank line.
v=input('Enter the volume of robot(m^3)= ');
disp('    ');
%
%
```

```
Condition=(Density_water*g*(v+deltav))
display('Please wait...');
%
%
display('The simulation result is:');
if Condition = (m*g)
   display('*****suspended*****');
else if Condition >(m*g)
      display('*****floating upward*****');
   else
      display('*****sinking downward*****');
   end;
end;
toc;
workspace;
disp(date);   % This MATLAB® function returns a string containing the date in dd-mmm-yyyy format.
```

****

Obstacle avoidance simulation (AVR, ATMEGA 32) [18-20]

```
#include <avr/io.h>
#include <util/delay.h>
#include <lcd.h>

#define US_PORT PORTA
#define US_PIN PINA
#define US_DDR DDRA
#define US_POS PA0
#define US_ERROR 0xffff
#define US_NO_OBSTACLE 0xfffe
uint16_t getPulseWidth()
{
		uint32_t i, result;

		for (i = 0; i<600000; i++)
		{
				if (!(US_PIN & (1 << US_POS))) continue; else break;
		}

		if (i == 600000)
				return 0xffff;

		TCCR1A = 0X00;
		TCCR1B = (1 << CS11);
		TCNT1 = 0x00;

		for (i = 0; i<600000; i++)
		{
				if (US_PIN & (1 << US_POS))
				{
						if (TCNT1 > 60000) break; else continue;
				}
				else
						break;
		}

		if (i == 600000)
				return 0xffff;
```

```
        result = TCNT1;

        TCCR1B = 0x00;

        if (result > 60000)
                return 0xfffe;
        else
                return (result >> 1);
}

void Wait()
{
        uint8_t i;
        for (i = 0; i<10; i++)
                _delay_loop_2(0);
}
void main()
{
        uint16_t r;


        Wait();

        LCDInit(LS_NONE);

        Wait();

        LCDClear();
        LCDWriteString("Ultra Sonic");
        LCDWriteStringXY(0, 1, "Sensor Test");

        Wait();
        Wait();
        Wait();
        Wait();
        Wait();
        Wait();
        LCDClear();

        while (1)
        {

                US_DDR |= (1 << US_POS);
                _delay_us(10);

                US_PORT |= (1 << US_POS);
                _delay_us(15);

                US_PORT &= (~(1 << US_POS));
                _delay_us(20);

                US_DDR &= (~(1 << US_POS));
                r = getPulseWidth();

                if (r == US_ERROR)
LCDWriteStringXY(0, 0, "Error !");
                else  if (r == US_NO_OBSTACLE)
                        LCDWriteStringXY(0, 0, "Clear !");
                else
```

```
                {
                        int d;

                        d = (r / 58.0);

                        LCDWriteIntXY(0, 0, d, 4);
                        LCDWriteString(" cm");

                        Wait();
                }
        }
}
```

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