New Worm Robot Structure Using the Shape-Memory Alloy

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ABSTRACT
This paper presents new designing for robot that moves like worm and the structure of this robot is made by the Shape-Memory Alloy (SMA). The smart alloys and the alloys in special kinds of artificial muscles apply motor action to the heat or coldness in the construction of artificial muscles. This robot is controlled by the operator and computer. Imaging, position of detection, smart guidance and environmental factors' estimation such as height and impact are other abilities for this robot.

KEYWORDS: Shape-Memory Alloy (SMA), Worm Robot Simulator, Artificial Muscles.

Nomenclature

v	Robot speed (m/sec)
m	Mass (kg)
g	Earth gravitation (N/kg)
f_s	Spring elastic force (N)
μ_s	Constant factor (0.1)
N	Robot force (N)
R	Resistance (Ω)
W	Electric power (W)
I	Current (mA)
V	Voltage (V)
$R_{1,3}$ *and* R_2	Series resistance

1. INTRODUCTION

Mechanics engineering, electrical engineering and life sciences require a transplant to increase the connection between these two classes of science. Especially, to make a muscle which is a basic internal body part in animals, materials are needed which do their obligations like a muscle and furthermore its physical shape and method operations are close to the actual muscle [1]-[5]. In recent decades, more researches have been done toward robots that simulate animal's motion [6]-[11]. For this purpose, complex mechanical structures on the basis of rotator motion engines were formed. Due to the apply of the motor, the system in terms of weight, volume and even magnetic and electronic suitability has lots of depauperations, additionally complex mechanical computation incapacitate exact execution possibility and economical efficiency. But within the improvement of technology during these days, different ways in this field were discussed. After the invention of smart alloys, making smart fake muscles were upgraded. Alloys of the artificial muscle can be applied in the thermal reactions against heat or coldness [12], [14].

This kind of alloys has an initial form which is determined by the user or producer factory. If they go out of shape, the materials go back to its primary mood by heating. One of the methods to heat them is to pass electric current through them. By using these two important points, we can design Shape-Memory Alloy (SMA), which are controlled by the electrical signal in order to be more look like real muscle[12]-[14].

In this paper, the artificial muscles construction for the action of worm robots simulation has been presented. This robot with simulation of the worm motion performs other responsibilities like Positioning module with Global Positioning System (GPS), intelligent navigation using ultrasonic sensors, infrared, PIR, photo transistors and so that, with the aim of Micro-switch sensors, it measures environmental factors by using hygrometer sensors, thermometers, oxygen meters, pressure gauges, etc. Hall efficiency, uses sensors to determine the height of G, and impact assessment

This paper has been organized as follows: mechanical structure and motion of the robot are presented in part II, the third part will discuss control and imaging, the part IV shows the SMA and Finally, Part V shows applications and proposals.

2. MECHANICAL AND ROBOT MOVEMENT

2.1. Overall View

The comprehensive view is presented in Fig. 1. This robot contains three main parts, first part is composed of the following elements:

•Two washers
• Two-piece (arm) aluminum
• Torsion spring
• M5 screw and nut
• SMA wire bent to shape

The second part is composed of the following elements:
• Spring
• SMA wires to the teeth of a saw

The third part is composed of these elements:
• two washers
• Two-piece (arm) aluminum
• Torsion spring
• M5 screw and nut
• SMA wire bent to shape

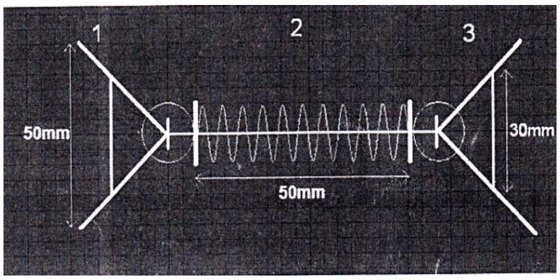

Fig. 1. The comprehensive view of robot

2.2. The Motion of the Robot

This robot's motion is divided into four cycles:

• The first step of motion:

This step is happened from 0 to 0.5 seconds (Fig. 2). At this step, the first and second parts have been become different. Fig. 3 and Fig. 4 show the modifications. The changes in first part occur due to flow and changing the mood of SMA (curved). Two arms of the aluminum distance from body of the tube separated from it. The changes in second part are occurred due to flow and changing the mood of SMA (toothy), but because time is 0.5 seconds, only half of the SMA returns to its primary form and it compacts the wire only 1cm (Fig. 4)

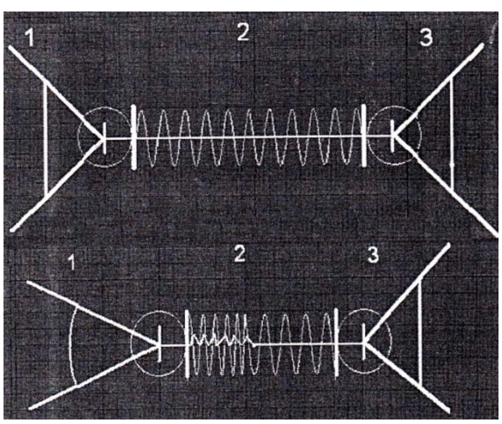

Fig. 2. The first step of motion

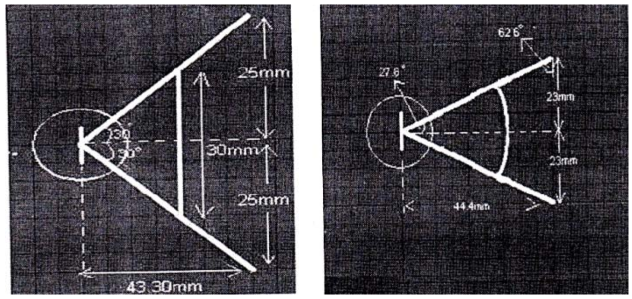

Fig. 3. The passing of the first movement at first part

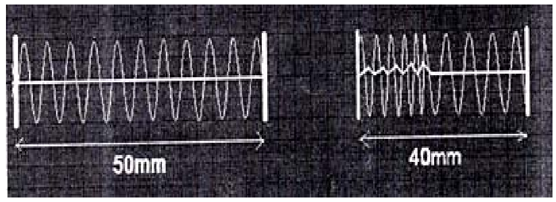

Fig. 4. Changes in the second part of the flow in the first stage

• The second step of motion:

This step is happened from 0.5 to 1 second (Fig. 5), at this step, the second part has been changed (Fig. 6).

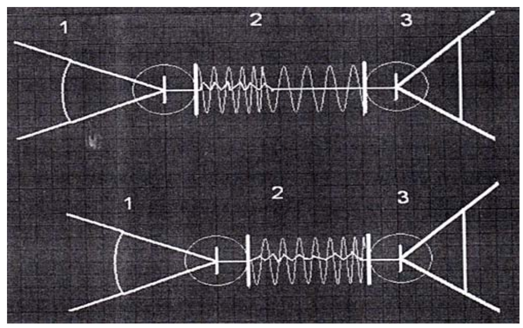

Fig. 5. The second step of motion

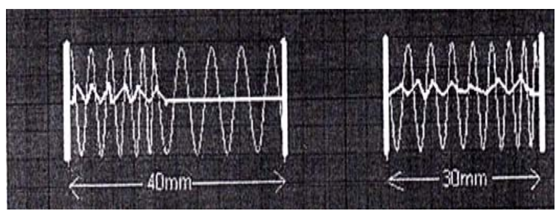

Fig. 6. The second part of the flow in the second step

• The third step of motion:

This step is happened from 1 to 1.5 seconds (Fig. 7). At this step, the first and third parts have been changed (Fig. 8-9). After the flow is disturbed, potential energy that was stored in the spring between the two arms of aluminum will force to SMA and will change the primary form of SMA, and then will change it into drawn-straight wire. Finally it causes two aluminum arms returning to the initial form.

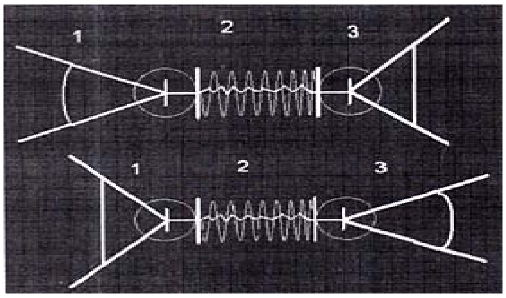

Fig. 7. The third step of motion

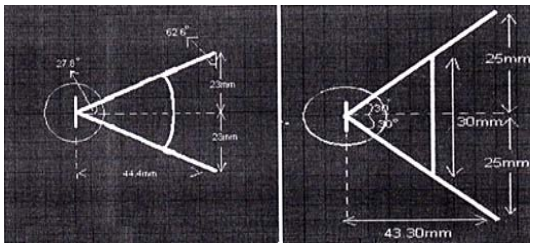

Fig. 8. The variation of the flow is stopped in the third step

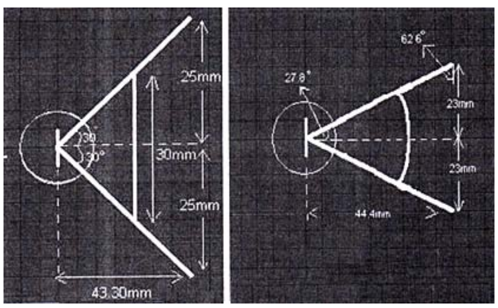

Fig. 9. The third part of the flow in the third step

The changes are occurred due to flow and changing the mood of SMA (curved). In this step, second part saves its state at the previous form.

• The fourth step of motion:
This step is happened from 1.5 to 2 seconds (Fig. 10). At this step, the second and third parts have been made different (Fig. 11-12). First, second and then third part with cut off flow return to the first condition

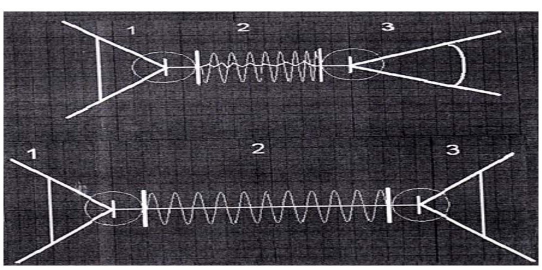

Fig. 10. The fourth step of motion

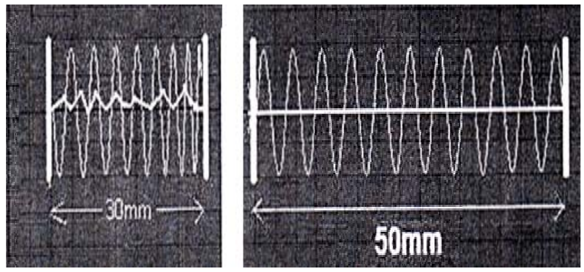

Fig. 11. The second part of the flow is stopped in the fourth step

When the current through the SMA in the second part is disconnected, potential energy that was stored in the spring that was generated for the state, changing of SMA to toothy form has been caused to SMA was changed from primary mood and it becomes the wire length of 5 cm (Fig. 12).

After the flow is disturbed, potential energy that was stored in the spring between the two arms of aluminum will force to SMA and change the primary form of SMA, and then change it into drawn-straight wire. Finally, it causes two aluminum arms return to the initial form.

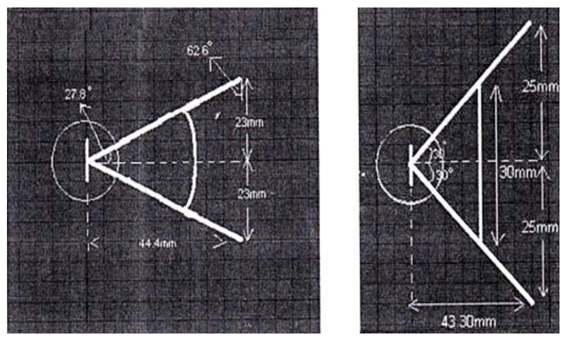

Fig. 12. Changes in the third part in fourth stage

According to these details, this robot moves 2 cm in 2 seconds then robot speed is equal to (1), so that weightening the various elements are shown in Table I:

$$v=\frac{2cm}{2s}=1\frac{cm}{s}=0.01\frac{m}{s} \tag{1}$$

The physical power of robot is like (2):

$$\begin{aligned} &mg = 2f_s \Rightarrow 1.15 = 2f_S \Rightarrow f_s = 0.575 \\ &f_s = \mu_s.N \Rightarrow 0.575 = 0.1\,N \Rightarrow N = 5.75 \end{aligned} \tag{2}$$

At third part of robot (Front of the robot) exists, two batteries with the camera and at first part of robot (back of the robot) a battery is applied with other electrical elements. Covering is important for the protection of elements and material in the circuit and body. It must cover materials of the robot in their position, perfectly and it must prepare appropriate protection against the penetration of the fluids and sediments in the robot and make proper insulation for balance the internal temperature of the robot. SMAs are sensitive to heat in the robot, they must isolate from thermal. In addition to all these instances, that are for the protection of the robot, this cover should work without any limitation of motion and flexibility for robot. Hence, according to the research on materials, Silicon is considered as the most suitable choice. This material has a lower weight density and it is excellent insulation against the influence of fluid and sediment. If appropriate format be done, it can maintain flexibility of the robot very good. In Fig. 13 an example of proper format is shown, finally, full view of the robot with a silicon coating is shown in Fig. 14.

Table.1. Weight the various elements

Element name	battery	camera	electronic components	washer / bolt / nut	sma wire and spring	pieces of aluminum	the robot	part I	part II	part III
Weight (gr)	20	8	20	7	10	2.16	113.64	49.82	6	57.82

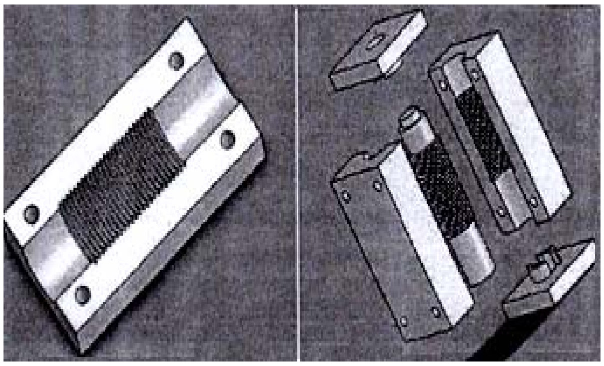

Fig. 13. An example of proper form

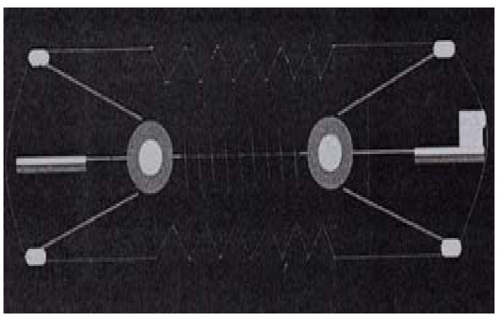

Fig. 14. Full view of the robot with a silicon coating

3. CONTROL AND IMAGING

In this part control of robot using wireless operators, imaging and picture transfer by robot will be described. In controlling, operators transfer motor instruction to the robot by computer and MATLAB software without wires and subsequently robot with the proper pulse and the supply of electrical power essential of SMA, depending on control commands controls type of movement. In imaging and transfer image of the robot to computer, it is trying to clear and precise picture and yet imaging instruments contain low weight and become small.

3.1. Robot Control

The block diagram of robot control is presented in Fig. 15. First part is sending commands' movement in MATLAB. In second part, USB protocol via IC FT232 change to serial protocol. In third and forth parts, wireless communication is established between the user and the robot by transmitter - receiver serial. The fifth part that is main operating of robot composes microcontrollers with the following tasks:

• Receive and analyze the code
• Production control pulses for motion control and optimal motion

Sixth part shows electrical calculations needed to SMA launch.

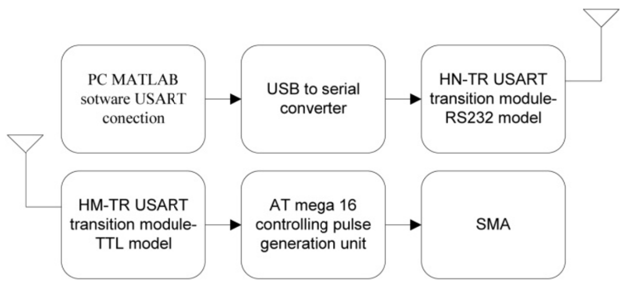

Fig. 15. The block diagram of robot control

3.2. Imaging Part

In this part, the small transmitter camera with 2.4 GHz and the weight of 8 grams are used. The camera is 1000 × 1000 pixels, contains the AV output and interface with laptop within using capture card. This card changes AV signal to the USB protocol. After transferring the images to the computer, the images will be displayed in MATLAB. It is necessary to mention that, for better visible imaging, light LED and infrared light are used in the camera, Fig. 16 shows a block diagram of this section and Fig.17 shows the camera position on the robot.

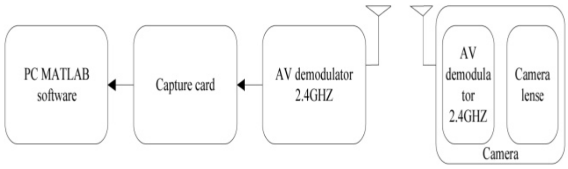

Fig. 16. Block diagram of the robot imaging

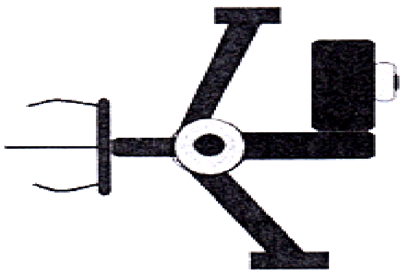

Fig. 17. Camera position on the robot

3.3. Computing Elements

According to the study on different types and the advantages and disadvantages of each type, the SMA wire cord with No. 125 as the base for the robot is chosen, the electrical and physical data are as follows:

$$R\left(\frac{\Omega}{m}\right)=70\ \frac{\Omega}{m}$$
$$W\left(\frac{w}{m}\right)=4.4\ \frac{w}{m} \tag{3}$$
$$\text{The maximum closing force}=7.36\ N$$
$$\text{The maximum opening force}=0.43\ N$$

In accordance with data for SMA wire 125, electrical identifications of three pieces of SMA wire that are used in the robot are following as:

$$\begin{aligned} &SMA\ 1{,}3\ (Hook): \\ &R=70\times 0.03=2.1\ \Omega \\ &I=250\ mA \\ &W=4.4\times 0.03=0.1\ w \\ &V=2.1\times 250\ mA=0.525\ v \end{aligned} \tag{4}$$

$$\begin{aligned} &SMA\ 2\ (Body): \\ &R=70\times 0.05=3.5\ \Omega \\ &I=250\ mA \\ &W=4.4\times 0.05=0.88\ w \\ &V=3.5\times 250\ mA=0.875\ v \end{aligned} \tag{5}$$

Since the power supply is 9v so that 0.525v is needed for the hook SMA and 0.875v is needed for body SMA, so we should use series' resistance with SMA to achieve an appropriate voltage level-Resistances are calculated as follows:

$$\begin{aligned} &R_{1,3}: 9\ V\times\frac{2.1\ \Omega}{2.1\ \Omega+R_1}=0.525\ V\Rightarrow R_{1,3}=33.9\ \Omega \\ &R_2: 9\ V\times\frac{3.5\ \Omega}{3.5\ \Omega+R_2}=0.875\ V\Rightarrow R_2=32.5\ \Omega \end{aligned} \tag{6}$$

4. SHAPE MEMORY ALLOY (SMA)

The initial transcript steps towards finding of the shape-memory effect were taken in the 1930s. According to Otsuka and Wayman, A. Ölander discovered the pseudo elastic performance of the Au-Cd alloy in 1932. Greninger and Mooradian (1938) observed the formation and disappearance of a martensitic phase by decreasing and increasing the temperature of a Cu-Zn alloy. The primary phenomenon of the memory effect was supervised by the thermoplastic behavior of the martensite phase and it was widely reported a decade later by Kurdjumov and Khandros (1949) and also by Chang and Read (1951) [15].

The nickel-titanium alloy was improved in 1962–1963 by the United States Naval Ordnance Laboratory and has been commercialized under the trade name Nitinol (an acronym for Nickel Titanium Naval Ordnance Laboratories). Their extraordinary characteristics were discovered by chance. One of the associate technical directors, Dr. David S. Muzzey at a laboratory management meeting, wanted to know what would occur if the sample was subjected to heat and held his pipe lighter underneath it. To everyone's amazement the sample stretched back to its original shape [16], [17].

There is another type of SMA, called a Ferromagnetic Shape-Memory Alloy (FSMA), which changed shape by powerful magnetic fields. These materials contain particular interest while the magnetic response tends to be faster and more efficient than temperature-induced responses [18]-[21].

Metal alloys are not the only thermally-responsive materials; shape-memory polymers have also been developed, and become commercially available in the late 1990s.

Many metals have various crystal structures at the same composition, but most metals do not show this shape-memory effect. The exceptional property that allows shape-memory alloys to return to their primary shape after heating is that their crystal transformation is fully reversible. In most crystal transformations, the atoms in the structure will move through the metal by distribution, changing the composition locally, even though, the metal as a whole is made of the same atoms. A reversible transformation does not include this diffusion of atoms, instead the entire atoms shift at the same time to form a new structure, much in the way a parallelogram can be made out of a square by pushing on two opposing sides. At different temperatures, different structures are favored and when the structure is cooled through the transition temperature, the martensitic structure forms from the austenitic phase. SMA can show three-phase crystal: Austenite, Martensite and R. Phase [12]-[14].

Within the memory effect, sample is formed in a specific amount Martnzy, with heating it and then backing to Austin, The sample backed to the first condition. Research on the solid-state metallurgical sample shows the arrangement of atoms without any changing in the composition of the phases and this change has led to the formation of new phase and stable crystalline structure. Progress without the need for change and movement of the separate atoms can be considered independent of time and so the temperature dependence is considered as only factor that shows the progress of this change.

Transformation from Austenite to Martensite can be investigated in three stages:

• Determine network form
• Heterogeneous cutting
• Network rotation

Memory alloys have many mechanical characteristics in each temperature. Martensite changing is seen with few percent strain and relatively low pressure stress. While the austenite in high temperature needs relatively large stress for deformation.

5. SUGGESTION FOR THIS ROBOT

● Users can apply GPS on this robot for smart navigation.

● Users can install sensors: dampness meter, thermometers, oxygen meters, pressure meter, hall effect and etc.

● Automatic navigation by ultrasonic sensors, infrared, PIR, photo transistors are the other applications of this robot.

6. CONCLUSION

New structure like worm robot using the Shape-Memory Alloy (SMA) has been shown in this paper. SMA wire with No. 125 has been selected. This worm robot has lots of applications specially it is used for imaging. Users Three main mechanical parts have been presented. Users control this robot by wireless system and MATLAB.

REFERENCES

[1] B., Tondu, R., Emirkhanian, S., Mathé and A., Ricard, **"A Ph-Activated Artificial Muscle Using the Mckibben-Type Braided Structure"**, *Sensors and Actuators A: Physical,* Vol.150, No.1, pp. 124-130, 2009.

[2] K.C., Wickramatunge, T., Leephakpreeda, **"Study on Mechanical Behaviors of Pneumatic Artificial Muscle"**, *International Journal of Engineering Science,* Vol.48, No.2,, pp.188-198, 2010.

[3] K., Takashima, J., Rossiter and T., Mukai, **"Mckibben Artificial Muscle Using Shape-Memory Polymer",** *Sensors and Actuators A: Physical*, Vol. 164, No. 1, pp. 116-124, 2010.

[4] J., Kim, S., Yun, Z., Ounaies**," Discovery of Cellulose as a Smart Material",** *Macromolecules,* Vol.39, No.12, pp 4202–4206, May 2006.

[5] T., Ross Kelly, **"Book Review of Intelligent Materials"**, *Journal of the American Chemical Society ,* Vol.130, No.20, pp. 6651–6652, April 2008.

[6] B., Gramescu, C., Nitu and N., Alexandrescu, **"Modeling of a Mobile Robot with Worm-like Movement",** *The International Conference on Computer as a Tool ~EUROCON*, Belgrade, Russia, November 21-24, 2005

[7] D., Zarrouk, I., Sharf and M., Shoham, **"Analysis of Wormlike Robotic Locomotion on Compliant Surfaces",** *IEEE Transactions on Biomedical Engineering,* Vol.58 ,No. 2, pp. 301-309, February 2011.

[8] H., Shin, K.M., Jeong and J.J., Kwon, **"Development of a Snake Robot Moving in a Small Diameter Pipe"**, *IEEE International Conference on Control Automation and Systems ~ICCAS 2010~*, October 27-30, 2010.

[9] K., Wang, Z., Wang, Y., Zhou and G., Yan, **"Squirm Robot with Full Bellow Skin for Colonoscopy",** *IEEE International Conference on Robotics and Biomimetics ~ROBIO 2010~,* Tianjin, China, 2010.

[10] J., Liu, **"Modelling and Online Optimization of Robotic Fish Behaviours"**, *Ph.D. dissertation, Dept. Elect. Eng., University of Essex,* United Kingdom, 2007.

[11] H., Hu, J., Liu, I., Dukes and G., Francis, **"Design of 3D Swim Patterns for Autonomous Robotic Fish",** *Proceedings of IEEE International Conference on Intelligent Robots and Systems*, Beijing, China, October 2006.

[12] B.K., Gu, Y.A., Ismail, G.M., Spinks, S.I., Kim, I. So and S.J., Kim, **"A Linear Actuation of Polymeric Nanofibrous Bundle for Artificial Muscles"**, *Chemistry of Materials,*Vol.21, No.3 ,pp. 511-515, 2009.

[13] M., Rajagopalan, I.K., Oh, **"Fullerenol-Based Electroactive Artificial Muscles Utilizing Biocompatible Polyetherimide"**, *ACS Nano,* Vol. 5 No. 3, pp. 2248-2256, February 2011.

[14] B., K. Juluri, A.S., Kumar, Y., Liu, T., Ye, Y.W., Yang, A.H., Flood, L., Fang, J.F., Stoddart, P.S., Weiss and T.J., Huang, **"A Mechanical Actuator Driven Electrochemically by Artificial Molecular Muscles"**, *ACS Nano,* Vol.3, No. 2,, pp. 291-300, January 2009.

[15] K., Otsuka, C.M., Wayman, **"Shape Memory Materials",** *Cambridge University Press*, 1999.

[16] G.B., Kauffman, I., Mayo, **"Memory Metal,"** *Chem Matters*, pp. 4-7, October 1993.

[17] W J., Buehler, **"WOL History Supplement NITINOL Re-Examination"**,[Online]. Available: www.wolaa.org, 2006

[18] F.A., Khalid, S.Z., Abbas, **"Characterization and Properties of Ferromagnetic Shape Memory Alloys"**, *Materials Characterization*, Vol.62, No.12, pp. 1134-1140, December 2011.

[19] G.F., Dong, W., Cai and Z.Y., Gao, **"Microstructure and Martensitic Transformation of Ni–Mn–Ga–Ti**

Ferromagnetic Shape Memory Alloys", *Journal of Alloys and Compounds,*Vol. 465, No.1, pp. 173-176, 2008.

[20] G.D., Liu, Z.H., Liu, X.F., Dai, S.Y., Yu, J.L., Chen and G.H., Wu, "**Investigation on Ferromagnetic Shape Memory Alloys"**, *Science and Technology of Advanced Materials,* Vol, 6 No. 7, pp.772-777, October 2005.

[21] H.Z., Song, H.R., Zeng, Y X., Li, Q R., Yin and X., Hu, **"Ferroic Domain Characterization of Ni55Mn20.6Ga24.4 Ferromagnetic Shape Memory Alloy"** , *Transactions of Nonferrous Metals Society of China,* Vol. 21, No. 9, pp. 2015-2019 , September 2011.