Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Modeling of serial link robots covered with a thin flexible film

Mizuho Shibata
Department of Robotics
Kindai University
1 Takaya Umenobe , Higashi-Hiroshima, Japan
shibata@hiro.kindai.ac.jp

Norimitsu Sakagami
Department of Navigation and Ocean Engineering
Tokai University
3-20-1 Orido, Shimizu-ku, Shizuoka, Japan
sakagami@scc.u-tokai.ac.jp

***Abstract*— This manuscript describes the modeling of a serial link robot covering with a thin, flexible film. By covering a serial link robot with a plastic film, the robot can manipulate daily goods such as foods and clothes cleanly. However, the mechanical properties of the serial links covering the film have not been clarified. In this manuscript, we discuss the fundamental mechanical characteristics, whether the film and the link should slide or not. We assume that the film is modeled as a beam, and analyze the static mechanical characteristics from the viewpoint of material mechanics. As a result, we find the robot can rotate even in a small DC motor by filling an appropriate volume of an insulating fluid. We evaluate the validity of the analyses experimentally through the prototype fabricated by the robot packaging method.**

***Index Terms*— Serial link robot, robot packaging method, vacuum packaging, flexible film**

I. Introduction

This manuscript describes the modeling of a serial link robot covering with a plastic film to establish design theory. In the industry which handles rigid objects such as logistics, the introduction of robots is advancing from the viewpoint of high accuracy and efficiency. However, in industries dealing with daily necessities such as food, clothing, and linen supplies, many tasks are still carried out manually [1]. In this background, there is a restriction that not only many of the objects to be handled contain water and are amorphous, but also dirt must not adhere to them. This problem is solved by wearing rubber gloves when handling daily necessities manually. Following this, it is considered that the work becomes possible by covering the flexible material such as rubber and resin film on the robot.

In the serial link robot covered with thin, flexible material, the fundamental mechanical characteristics have not been revealed, such as whether the material should slide or not. In this manuscript, we investigate two types of coverings: (1) coverings in which the link and the material do not slide during motion, and (2) coverings in which the link and the material slide during motion. Figure 1 shows the concept of a serial link robot in which the link and the covering material do not slide during motion. As shown in the figure, the link contacts firmly with the covering material. Figure 2 shows the concept of a serial link robot in which the link and the covering material slide during motion. We use a lubricant fluid between the link and the covering material in this concept. However, the lubricant fluid must be insulating because the drive circuit and power supply have conductive property.

In this paper, vacuum packaging technology is applied as a method to cover a serial link robot with thin, flexible material. Vacuum packaging technology is conventionally used in the food industry. In the food industry, foodstuffs are packed in plastic bags by defoaming and sealing [2]. We have developed a method of covering a serial link robot with a plastic film using a vacuum packaging machine [3], [4]. We call this method the robot packaging method. Using this fabrication method, we can select the contact state between the robot and the covering material by adjusting the volume of the insulating fluid to be filled within the robot. Besides, we can fabricate the two type of covering using the same material.

Several types of research on covering a robot with flexible/deformable materials such as conductive rubber and silicon have been conducted over the past decades. Several researchers flexible/deformable covers with a part of the robot, such as object manipulation by a soft finger [5], [6], humanoid with soft pad [7], [8], have been studied. As several types of research covering the whole of a robot with a flexible/deformable material, such as a mobile robot [9], a manipulator [10], a fish-like robot [11], and humanoids [12]–[14], have been studied. Most of these researches have been carried out for shock absorption and decoration using silicon. However, the robots covering by thin, flexible material and its design theory, especially the design theory considering sliding characteristics, are not established.

We have proposed a fish-like robot that uses a plastic film for the outer shell to fabricate a lightweight underwater robot with high-pressure resistance property [3], [4]. The internal components of this robot include an actuator, a driving circuit, a sensor, and an oscillating plate as a fin. After assembling the components as a link mechanism, the link is encapsulated with a plastic bag using a vacuum packaging

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

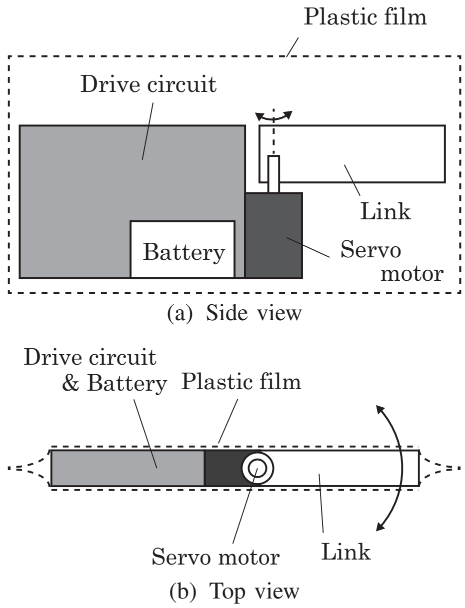


Fig. 1. Concept of serial link robot covered with thin flexible material

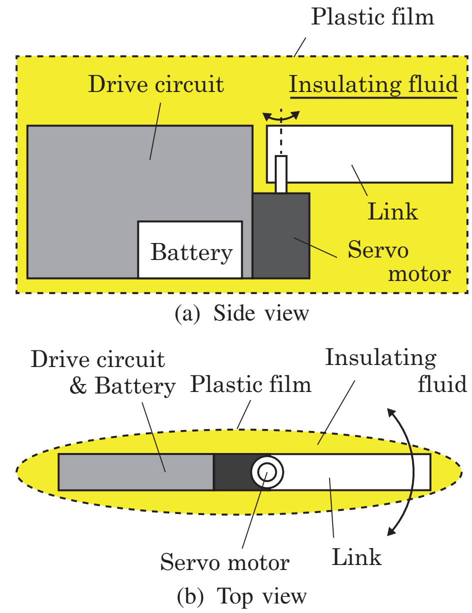


Fig. 2. Concept of serial link robot covered with thin flexible material (including insulating fluid)

machine. The oscillating plate is used inside the plastic film bag to obtain propulsion force in water (Figures 2 and 3). In general fish-like robots, soft materials such as silicone [11], rubber [15]–[17], polyvinyl chloride [18], and silica gel [19] are often used as outside waterproof containers. Our prototype has a lightweight body because the film is used as both a waterproof container and a thruster.

This paper consists of six sections. Section 2 represents the robot packing method. Section 3 describes a model of rotation without slippage for the links covering with a thin, flexible film. Section 4 describes a model of rotation with slippage for the links covering with a thin, flexible film. The film is modeled as a beam. Section 5 discusses experiments to verify the validity of analytical results. Chapter 6 concludes this manuscript.

II. Robot packaging method

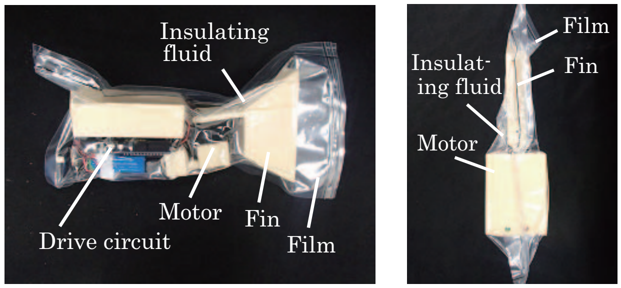
The proposed robot uses vacuum packaging technology to cover the outer shell of the robot with a plastic film. Figure 1 and Figure 2 show the components of the proposed robot. The method of encapsulating the components of a robot such as a servomotor and a drive circuit in a plastic bag is called a robot packing method [3]. By using a plastic bag for the outer shell, the entire robot can be made lighter. In this method, an insulating fluid improves the water-resistance and the pressure-resistance properties of the robot within the plastic film bag. The environment pressure deforms the insulating fluid and the film; therefore, the force caused by the differential pressure to the film bag does not generate. In principle, the outer shell in this robot is not destroyed by the differential pressure, and the pressure resistance property of the robot depends on that of the electronic circuit used in the component. Since electronic elements used in circuits generally have a small surface area, they have a small force against pressure and can withstand high environmental pressure. The technique to prevent the destruction of the outer shell of marine equipment by utilizing a flexible element such as rubber for a part of the outer shell is known as the equivalent method. This equivalent method is applied to a commercially available underwater robot [20] and a marine power source [21]. The entire outer shell of the equipment is a flexible element in the robot packaging method, which is a natural extension of the equivalent method.

The fabricating of the robot by the robot packaging method consists of the following four processes:

1) Put the assembled robot components into a plastic film bag.
2) Pour the insulating fluid into the plastic bag along with the components.
3) Defoam the bag in the chamber of a vacuum packaging machine.
4) After the defoaming, seal the bag by thermal welding.

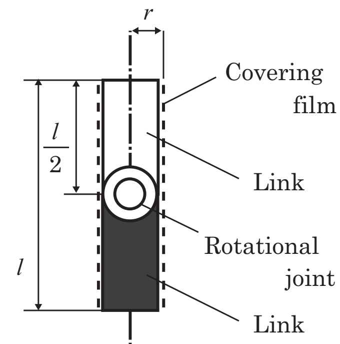
In the process (2), the amount of the insulating fluid is adjusted as necessary. In case we make the film contact firmly with the link, the insulating fluid is not used.

When a robot is covered with a flexible material such as silicon, several researchers have pointed out that a robot cannot generate a large force by the restoring force of the material itself [12]–[14]. Since the plastic film used as the outer shell in this method is extremely thin and has low

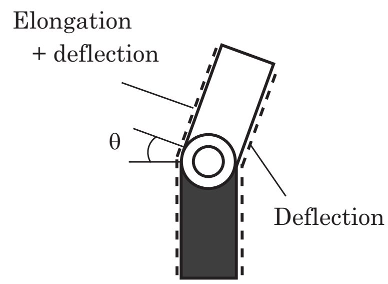


(a) Side view (b) Top view

Fig. 3. Fish robot encapsulated by a plastic film bag



(a) Initial state



(b) Rotational state

Fig. 4. Rotation of serial links with a plastic film

bending rigidity, it is expected that the driving force can be obtained even by a small-output motor. Besides, a non-contact sensor and a non-contact power supply device can be installed inside the robot due to the outer shell is made of a plastic film which has an electromagnetic wave-transmitting property [4].

III. Rational motion without slippage

A. Modeling

When a serial link robot is covered with a plastic film, the film can be firmly contacted with the surface of the robot by utilizing the vacuum packaging technology. In this section, we discuss the rotational motion of a film-covered serial link robot without slippage between the film and the robot. The film is utilized as a commercially available plastic film used in the food industry. We modeled the film statically from the viewpoint of the material mechanics, assuming that it can be elongated and deflected but not be shrunk. Figure 4 shows the modeling. In the initial state (Figure 4-(a)), the film is neither elongated nor deflected. Let $l,\ w,\ t,$ and E be the length, width, thickness, and Young's modulus of the film at the initial state, respectively. For simplicity, it is assumed that the links connected by an active rotational joint move in a plane. Let $l/2,\ 2r$ be the length and width of the links, respectively. When the film and the link firmly contact, and there is no slip, the torque for rotating the joint depends mainly on the torque τ_n for deflecting and elongating of the flexible film. Therefore, the torque τ_n describes as follows:

$$\tau_n = 2\tau_D + \tau_E, \tag{1}$$

where, τ_D, τ_E are the torque for elongating and deflecting of the flexible film, respectively.

For deflecting of the flexible film, assuming that the film is a cantilever beam loaded at the tip, the torque τ_D is expressed as the following equation using the rotation angle θ:

$$\tau_D = \frac{Ewt^3}{2l}\sin\theta. \tag{2}$$

For the elongation of the flexible film, the elongation is described as $r\theta$ using the rotation angle; therefore, the torque τ_E is described as follows, assuming that the length l elongates uniformly:

$$\tau_E = \frac{r^2 Ewt}{l}\theta. \tag{3}$$

When a plastic film is used as the covering material, we can select a material that the thickness is thinner than the width of the link. Therefore, the condition $\tau_E \gg \tau_D$ is satisfied from the condition $r \gg t$. When there is no slippage between the film and the link, the torque τ_E to elongate the film is dominant for the torque τ_n to rotate the joint of the serial link robot covered with the thin, flexible film. Hence, Eq. (1) is rewritten as follows:

$$\tau_n = \tau_E. \tag{4}$$

B. Numerical example

In this section, the validity of the results obtained in the previous section is discussed with a specific numerical example. Here, we take an example as the fin motion of an underwater robot covered with a flexible film. Figure 5 shows the prototype. The fin length of this prototype is 50 [mm]; therefore, the length l in our model becomes 100 [mm]. Plastic film used for general food packing is used in this prototype. The thickness t of the film is 50 [μm], and

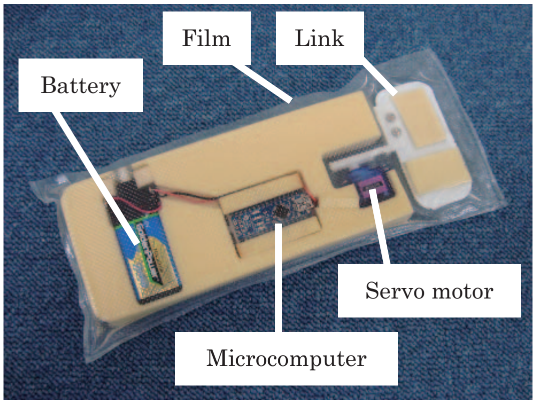


Fig. 5. Fish robot encapsulated by a plastic film bag for calculating a numerical example

Young's modulus E of the film is assumed as $4.5\,$[Pa]. The width of the prototype is $80\,$[mm] so that we approximate the width w of the film is $80\,$[mm]. Assuming the rotating angle θ is $\pi/6\,$[rad], the torque τ_D [Nm] to deflect the film is described as:

$$\tau_D = 1.9 \times 10^{-4}\,[\text{Nm}].$$

In addition, the thickness of the prototype is $20\,$[mm] so that we approximate the width r of the link is $10\,$[mm]. The torque τ_E [Nm] to elongate the film is described as:

$$\tau_E = 9.4\,[\text{Nm}].$$

As can be seen from this numerical example, when there is no slip between the link and film, the torque τ_E to elongate the film is dominant for the torque τ_n to rotate a joint of a serial link robot covered with a thin, flexible film. To realize the above numerical example by a DC motor, we need to select a motor of several $10\,$[W] or a motor with a high gear ratio. In any case, the size of the serial robot itself tends to become larger. According to Eq. (3), since the torque τ_E is proportional to the square of the parameter r related to the thickness of the serial link robot, the actuator size tends to be larger. Besides, many films have a plastic property to elongation. From this viewpoint, it is not a practical design method to realize motion without slippage between the link and the film.

IV. Rational motion with slippage

A. Modeling

When a serial link robot is covered with a flexible film, a fluid can act as a lubricant. In our fabrication method, an insulating fluid is filled between the link and the film to improve the waterproof property. In this section, we investigate the rotational motion of a serial link robot covered with a flexible film when there is a slippage between the link and the film. As in the previous section, we utilize the plastic film used in the food industry in our prototype. Figure 6 shows the modeling. From the initial state (Figure 4-(a)), the link rotates under the frictional force of the film. In this section, we assume that the film is a beam that cannot elongate and shrink during the sliding motion. Besides, we assume that the film has a sufficient length for sliding motion.

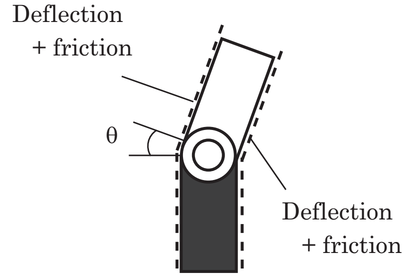


Fig. 6. Rotation state considering with slippage between the link and film

The torque τ_s for rotating the active joint during the slip motion depends on the torques τ_D and τ_F caused by the elongating force and the frictional force, respectively. Therefore, the torque τ_s is as the following equation:

$$\tau_s = 2\tau_D + 2\tau_F, \tag{5}$$

where μ and P are the frictional coefficient and the pressure between the link and the film. The torque τ_F is as follows:

$$\tau_F = \mu P l w r. \tag{6}$$

According to Eqs. (2), (5) and (6), the torque τ_s to rotate the joint of a serial link robot covered with a thin flexible film is dominant to either the torque τ_D or the torque τ_F, depending on the friction coefficient.

In the field of tribology, it is known that the friction coefficient depends on the viscosity, sliding speed, load, and thickness of lubricant between sliding objects. This relationship is called the Stribeck curve [22]. Based on the curve, according to the liquid quantity of the insulating fluid to be encapsulated, the thickness of the lubricant between the film and the link can change in a serial link robot fabricated by our robot packing method. Therefore, the torque τ_s to rotate the joint depends on the friction coefficient when there is a slip between the covered plastic film and the link.

B. Numerical example

In this section, the validity of the results obtained in the previous section is discussed with a specific numerical example. We also utilize the prototype of the previous chapter as an example. We assume that the pressure applied to the film and the link is atmospheric pressure. Thus, the pressure

P is 1.0×10^5 [Pa]. Assuming that the friction coefficient μ is 0.1, the torque caused by the friction force is:

$$\tau_F = 8.0 \times 10^{-1} \text{ [Nm]}.$$

If the coefficient of friction is low enough, the joint will be able to rotate under friction.

Assuming that the rotation angle of the link is $\pi/6$ [rad], the friction of coefficient μ when the torque τ_D [Nm] caused by the deflection corresponds with the torque τ_F [Nm] caused by the friction is described as follows:

$$\mu = 2.4 \times 10^{-5}.$$

If the coefficient of friction is smaller than this value, the condition $\tau_F < \tau_D$ is satisfied.

V. Experiment

In this section, we experimentally evaluate the relationship between the amount of fluid and the rotation angle of a serial link robot covered with a plastic film.

A. Measuring system

The measuring system is 233 [mm] length, 80 [mm] width, 18 [mm] thickness, and 146.3 [g] weight (Figure 7). We used a servomotor SG51R (made by TowerPro) to an actuator for rotating the link. We also used a rectangular dry battery 9 [V] as the power source, and a polymer foam (Co-polymer foam, 250 [m] specification, specific gravity 0.2, made by NiGK Corporation) for the body. A magnetic encoder module with AS5048A (made by AMS) was used as an angle sensor to measure the rotation of the link. Two microcomputers (Arduino Nano 3.1) were used. One was used to drive a servo motor, and the other was used to save the measuring data. Nylon poly TL type 12-38 (made by Fukusuke Kogyo Co., Ltd.) as the packaging film, and fluorinate FC-3283 (made by 3M, specific gravity approximately 1.8) as the insulating fluid to be filled in the prototype.

The components of the measuring system, including the polymer foam of the body, and the plastic film did not adhere. The physical properties of the plastic film are the bending rigidity of 0.31 [gf·cm^2/cm], and the tensile work per unit area of 3.2 [gf·cm/cm^2]. These physical properties were measured based on the Kawabata's Evaluation System (KES) [23], [24]. The thickness of the film was 50 [μm]. The film was welded thermally in the chamber of the vacuum packaging machine (TM-HV made by Furukawa Mfg. Co., Ltd.) after the defoaming process. The time for the defoaming process was 30 [s], and the time for the thermal welding was 4 [s].

B. Experimental procedure

The target angle of the servo motor was set to $\pi/6$ [rad]. We fix the measuring system with a clamp so that the link of the measuring system faces downward (Figure 8). The film was thermally welded at the position 90 [mm] long from the opening of the film bag. After the packaging, we cut the film with 70 [mm] long from the opening of the film bag. We prepared the insulating fluid up to 100 [ml] in 10 [ml] increments and up to 200 [ml] in 20 [ml] increments. Besides, we checked the insulating fluids of 250 [ml]. We also measured the rotation angle of the link three times for each volume of the insulating fluid.

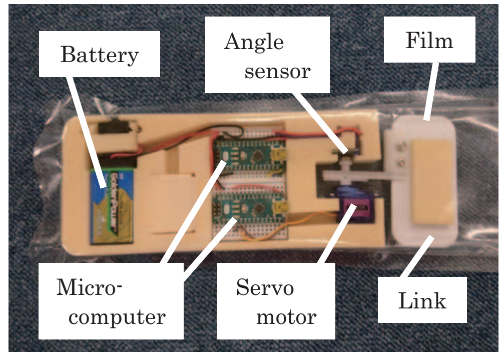


Fig. 7. Measuring system

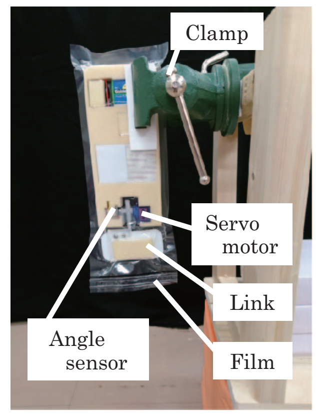


Fig. 8. Exprimental setup

C. Experimental results

Figure 9 shows the relationship between the volume of the insulating fluid and the rotation angle. The scatter plots were depicted based on the mean values of the experimental results. The maximum and minimum angles of each angle are represented as the error bars. As shown in the figure, the link rotated when the amount of the insulating fluid was 60 [ml]; therefore, we found that 50-60 [ml] was the lower limit volume of the insulating fluid to need for rotating the link in this measuring system. The rotating angle increased as the volume of the insulating fluid increased, and almost saturated at a constant value. The rated torque of the servo motor in this measuring system was 5.9×10^{-2} [Nm]. According to Eq. (3), the plastic film cannot be elongated by this servomotor; therefore, it is considered that the link is driven while sliding

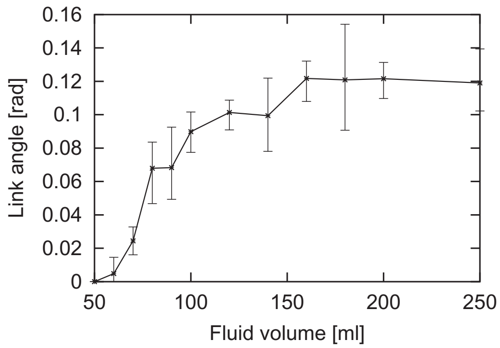


Fig. 9. Experimental result

by filling with the insulating fluid. The mass of the entire robot depends on the mass of the insulating fluid to be filled. From the viewpoint of volume reduction and mass reduction of the entire robot, the amount of insulating fluid should be small. The experimental results suggest that an appropriate amount of insulating fluid should be selected to drive the serial link robot covered with a plastic film depending on the rotating angle.

VI. Conclusion

This manuscript described the modeling of the film on the rotational motion of serial link robots covered with a thin, flexible film. This mechanism comprised active rotating joints with a plastic filmed bag. A vacuum packaging machine encapsulated the joint. The conclusions are as follows:

- When there is no slip between the covered plastic film and the link, the torque needed to stretch the plastic film is the dominant torque to rotate the link.
- When there is a slip between the covered plastic film and the link, the torque to rotate the link depends on the friction coefficient.
- The serial link robot covered with thin, flexible film can realize the rotary motion even in a small DC motor by filling an insulating fluid.

This manuscript presented a fish-like underwater robot with a single joint as an application of serial link robots covered with a thin, flexible film. The expansion to multi-joint serial robots such as robot hands, robot arms, snake-like mobile robots is a future problem to be solved.

Acknowledgment

This research was partially supported by Furukawa Mfg. Co., Ltd. This work was also supported by JSPS KAKENHI Grant Number JP19K04317.

References

[1] M. Shibata, T. Ota, S. Hirai: "Wiping motion for deformable object handling, " Proc. of 2009 IEEE International Conference on Robotics and Automation, pp. 134–139, 2009.

[2] R. Ahvenainen: "Novel Food Packaging Techniques," Woodhead Publishing, 2003.

[3] M. Shibata and N. Sakagami: "Fabrication of A Fish-like Underwater Robot with Flexible Plastic Film Body," Advanced Robotics, Vol. 29, Issue 1, pp. 103–113, 2015.

[4] M. Shibata: "Fish-Like Robot Encapsulated by a Plastic Film", Recent Advances in Robotic Systems, InTech, pp. 235–251, 2016.

[5] T. Inoue, S. Hirai: "Elastic Model of Deformable Fingertip for Soft-fingered Manipulation, " IEEE Transaction on Robotics, Vol. 22, No. 6, pp. 1273–1279, 2006.

[6] S. Arimoto, K. Tahara, M. Yamaguchi, P.T.A. Nguyen and H.Y. Han: "Principle of superposition for controlling pinch motions by means of robot fingers with soft tips, " Robotica, Vol. 19, No. 1, pp. 21–28, 2001.

[7] K. Fujiwara, F. Kanehiro, S. Kajita, K. Yokoi, H. Saito, K. Harada, K. Kaneko, H. Hirukawa: "The first human-size humanoid that can fall over safely and stand-up again, " Proc. of 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1920–1926, 2003.

[8] G. D. Magistris, A. Pajon, S. Miossec, A. Kheddar: "Humanoid walking with compliant soles using a deformation estimator, " Proc. of 2016 IEEE International Conference on Robotics and Automation, pp. 1757–1762, 2016.

[9] N. Mitsunaga, T. Miyashita, H. Ishiguro, K. Kogure, N. Hagita: "Robovie-IV: A Communication Robot Interacting with People Daily in an Office, " Proc. of 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 5066–5072, 2006.

[10] T. Morita, S. Sugano: "Double safety measure for human symbiotic manipulator, " Proc. of IEEE/ASME International Conference on Advanced Intelligent Mechatronics, pp. 130, 1997.

[11] H. Sumoto and S. Yamaguchi: "Development of a Motion Control System Using Phototaxis for a Fish Type Robot, " Proc. of the Int. Offshore and Polar Engineering Conference, pp. 307–310, 2010.

[12] M. Hayashi, T. Sagisaka, Y. Ishizaka, T. Yoshikai, M. Inaba: "Development of functional whole-body flesh with distributed three-axis force sensors to enable close interaction by humanoids, " Proc. of Int. Conf. on Intelligent Robots and Systems, pp. 3610–3615, 2007.

[13] K. Kobayashi, T. Yoshikai, M. Inaba: "Development of humanoid with distributed soft flesh and shock-resistive joint mechanism for self-protective behaviors in impact from falling down, " Proc. of Int. Conf. on Robotics and Biomimetics, pp. 2390–2396, 2011.

[14] T. Aono and Y. Nakamura: "Design of humanoid with insert-molded cover towards the variety of exterior design of robots, " Proc. of Int. Conf. on Intelligent Robots and Systems, pp. 3342–3347, 2005.

[15] C. Zhou, Z. Cao, Z.G. Hou, S. Wang and M. Tan: "Backward swimming gaits for a carangiform robotic fish, " Neural Computing and Applications, Vol. 23, Isuue 7-8, pp. 2015–2021, 2013.

[16] Y. Hu, L. Wang, J. Yu, J. Huo and Y. Jia: "Development and control of dolphin-like underwater vehicle, " Proc. of American Control Conference, pp. 2858–2863, 2008.

[17] P. Kodati, J. Hinkle, A. Winn and X. Deng: "Microautonomous robotic ostraciiform (MARCO): Hydrodynamics, design, and fabrication, " IEEE Transactions on Robotics, Vol. 24, Issue 1, pp. 105–117, 2008.

[18] J. Liu, I. Dukes and H. Hu: "Novel mechatronics design for a robotic fish, " Proc. of International Conference on Intelligent Robots and Systems, pp. 807–812, 2005.

[19] F. Shen, C. Wei, Z. Cao, D. Xu, J. Yu and C. Zhou: "Implementation of a multi-link robotic dolphin with two 3-DOF flippers, " Journal of Computer Information System, Vol. 7, pp. 2601–2607, 2011.

[20] Seabotix, http://www.seabotix.com/index.html

[21] D. A. White: "Modular Design of Li-Ion and Li-Polymer Batteries for Undersea Environments, " Marine Technology Society Journal, Vol. 43, No. 5, pp. 115–122, 2009.

[22] I. Hutchings, P. Shipway: Tribology: Friction and Wear of Engineering Materials 2nd Edition, Butterworth-Heinemann, 2017.

[23] S. Kawabata, M. Niwa: "Fabric Performance in ClothingManufacture, " Journal Textile Institute, Vol. 80, pp. 19–50, 1989.

[24] R. J. Harwood, P. J. Weedall, C. Carr: "The use of the Kawabata Evaluation Systemfor product development and quality control, " Journal of the Society of Dyers and Colourists, Vol. 106, No. 2, pp. 64–68, 1990.