The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Experimental Evaluation of a Flexible Joint Driven by Water Pressure for Underwater Robots

Mizuho Shibata, Yuusuke Onishi, and Sadao Kawamura

***Abstract*— We describe here the development a joint mechanism for underwater robotic manipulators. Arms of underwater robots require small-scale bodies and high waterproofing properties. In most of underwater robots, electric motors are used as actuators to drive the robotic arm/arms, but using electric motors for underwater manipulators may be problematic due to the size/weight of the robotic arm and need to waterproof the electric motors. We develop a joint mechanism composed of combinations of rigid and flexible members, which can be deformed by a prismatic actuator fixed onto two rigid parts. We utilize a leaf spring as the flexible joint and a McKibben actuator driven by water hydraulic pressure as the prismatic actuator. The number of members in this mechanism is smaller than that of a mechanism composed of a combination of one pulley and one coil spring. One advantage of this mechanism is the avoidance of gears, thus eliminating sliding parts from the joint.**

I. Introduction

Many expert divers inspect the bottoms of ships and maintain immersed structures such as water pipes under water. Their working efficiencies are quite low, because the use of air bottles limits diving time and even expert divers cannot work easily at depths below about 20 m. These tasks may be better performed by robotic systems, both for efficiency and safety reasons. Lightweight underwater robots with manipulators may be used to perform the dexterous tasks currently performed by expert divers. Over the past few decades, there have been several studies of underwater robots with manipulators (Underwater Vehicle-Manipulator System; UVMS) in terms of the control schemes [1], [2], [3], [4], [5], [6]. Our group has also developed an underwater robot with two manipulators (Figure 1) instead of two human arms [7]. In most of these robots, electric motors are used as actuators to drive the robotic arm/arms, but using electric motors for underwater manipulators may be problematic due to the size/weight of the robotic arm and need to waterproof the electric motors. Actuators under water are often attached to magnetic couplings, which are highly waterproof, but the addition of a magnetic coupling increases the size of the joint because of the mechanism itself. We have utilized a leaf spring as the flexible joint and a McKibben actuator driven by water hydraulic pressure as the prismatic actuator.

M. Shibata is with the Department of Robotics, Ritsumeikan Univ., 1-1-1 Noji-Higashi, Kusatsu, Shiga, 525-8577, Japan mizuho-s@se.ritsumei.ac.jp
Y. Onishi is with the Department of Robotics, Ritsumeikan Univ., 1-1-1 Noji-Higashi, Kusatsu, Shiga, 525-8577, Japan rr001067@ed.ritsumei.ac.jp
S. Kawamura is with the Department of Robotics, Ritsumeikan Univ., 1-1-1 Noji-Higashi, Kusatsu, Shiga, 525-8577, Japan kawamura@se.ritsumei.ac.jp

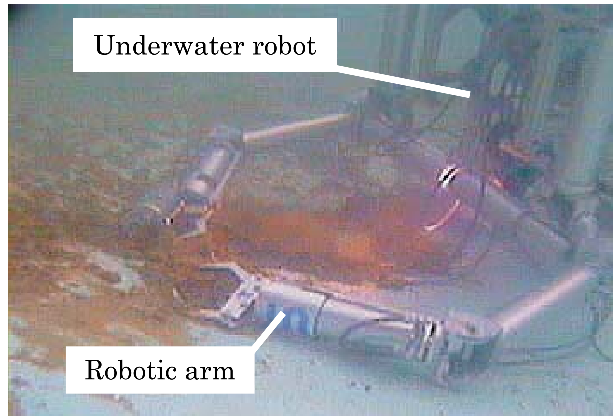


Fig. 1. Underwater robot with two arms driven by electric motors

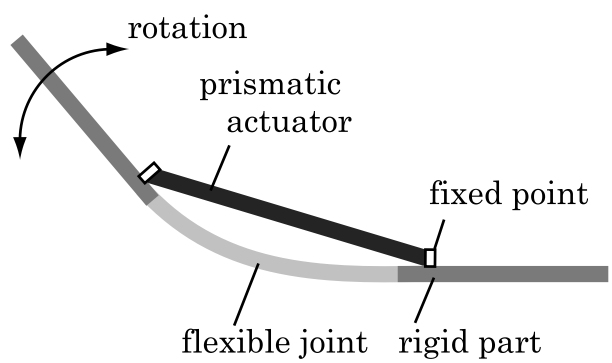


Fig. 2. Concept of flexible joint mechanism driven by prismatic actuator

We have developed a joint mechanism to simulate an arm of an underwater robot with a small-scale body and high waterproofing properties. The joint mechanism is composed of combinations of rigid and flexible members, which can be deformed by a prismatic actuator fixed onto two rigid parts (Figure2). This paper focuses on prototyping and controlling the joint mechanism. This mechanism automatically restores to its original state in response to deformation allowing use of just one prismatic actuator to adduct its joint. The number of members in this mechanism is smaller than that of a mechanism composed of a combination of one pulley and one coil spring. In addition, the flexibility in this mechanism yields high compliance against contact with an unplanned environment.

Several hydrostatic actuators have been proposed, including a hydrostatic transmission actuator fabricated to realize

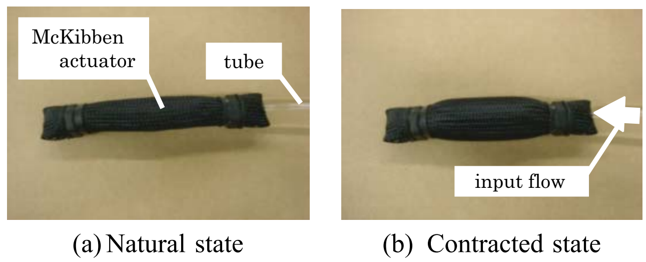


Fig. 3. McKibben actuator

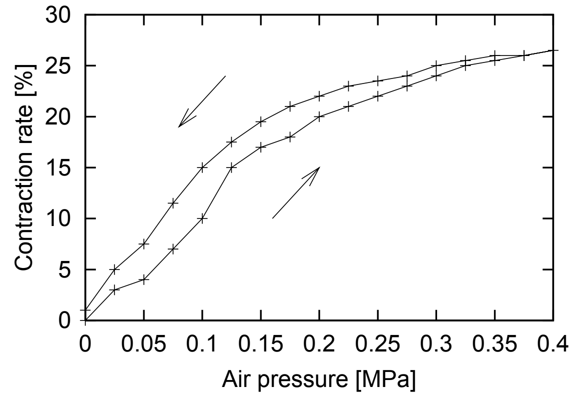


Fig. 4. McKibben actuator driven by air flow

an application of a humanoid robot [8]. We have utilized a leaf spring as the flexible joint and a McKibben actuator [9], [10], [11], [12] driven by water hydraulic pressure as the prismatic actuator. We developed a pump connecting two pumps in series to drive the McKibben actuator when under water. We describe the characteristics of the proposed joint mechanism, including the thickness and length of the flexible joint. Finally, we show the applicability of the joint mechanism by its use in a master-slave system.

II. Flexible joint mechanism

The joint mechanism we propose is driven by water hydraulic power and has partial flexibility. Usage of flexible material as a joint part decreases the number of parts required in the joint mechanism. Each joint mechanism is composed of two rigid links and one flexible joint which is restored to its original state in response to deformation, allowing each joint to be adducted by a single prismatic actuator (see Figure 2). We utilized a McKibben actuator driven by water hydraulic pressure. The combination of a reduced number of parts in the joint mechanism and an actuator driven by water pressure results in a smaller-scaled arm that includes the joint and is highly waterproof.

Several flexible link mechanisms have been described, including flexure hinges [13], [14], [15] and a flexible microarm [16], in which the mechanisms are made from homogeneous materials and therefore have geometric flexibility. Electrorheological (ER) fluids enhance the compliance properties of flexible joints [17], [18]. Our group has also utilized a joint mechanism with compliance in the construction of a robotic hand [19], [20]. This joint mechanism included a viscoelastic object and soft actuators in place of the cartilage and muscles of a human arm, respectively. We describe here the application of material flexibility to this mechanism.

One advantage of this mechanism is the avoidance of gears, thus eliminating sliding parts from the joint. Many floating objects, including algae, are present under water and may foul joints that include gears. Avoiding gears simplifies the maintenance of the mechanism. The avoidance of gears, however, is also one of the disadvantages of this mechanism. The arm including the joint generates a low force, which is increased by applying a McKibben actuator.

III. Design of joint mechanism

In this section, we describe the design of a flexible joint mechanism, including a water pump that drives the McKibben actuator under water. We also confirm the relationships among the range of moving angles and the characteristic of the flexible parts.

A. McKibben actuator

We utilized McKibben actuators (diameter; 2.54cm, Kanda Tsushin Kogyo Co. Ltd., Japan) as prismatic actuators to drive the flexible joint mechanism (Figure 3-(a)). The ratio of the generative force to the weight of the McKibben actuators was higher than that of electric motors of the same size. In general, the application of air flow to a McKibben actuator causes contraction of its body (Figure 3-(b)), although McKibben actuators driven by water pressure have been proposed [11]. These McKibben actuators driven by water flow should be able to work under water. Figure 4 shows the contraction rate of a McKibben actuator driven by air flow. The range of moving angles of the joint mechanism was dependent on the contraction rate, with higher contraction rates resulting in larger angles. The input air pressure required to drive a McKibben actuator to the desired contraction rate of 20% is about 0.25 MPa, regardless of the hysteresis loop of the McKibben actuator (Figure 4).

B. Water pump driving the McKibben actuator

In developing a water pump to drive the McKibben actuator, we applied bilge pumps (rule800; ITT Corporation, USA), each of which has a maximum output water pressure of about 0.15 MPa. Since the output pressure of one bilge pump cannot drive a McKibben actuator to a contraction rate of 20%, we connected two of these pumps in series, in which the output water flow of one pump is the input flow of the other pump. Figure 5 shows the relationship between pressure and input voltage for one pump and for two pumps coupled in series. At the same voltage, the series-coupling pump generated higher water pressure, sufficient to drive the McKibben actuator. The range of the hysteresis loop of the actuator driven by water flow was larger than that of

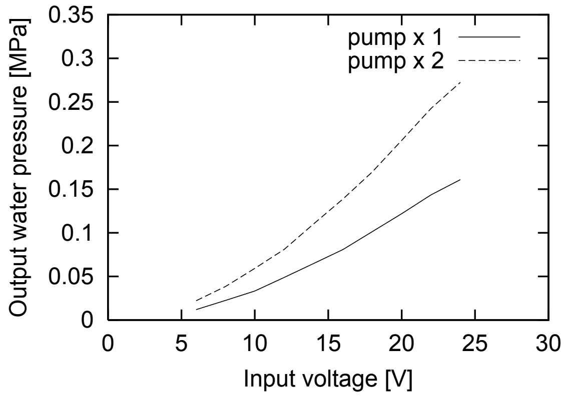


Fig. 5. Pressure characteristics of water pumps

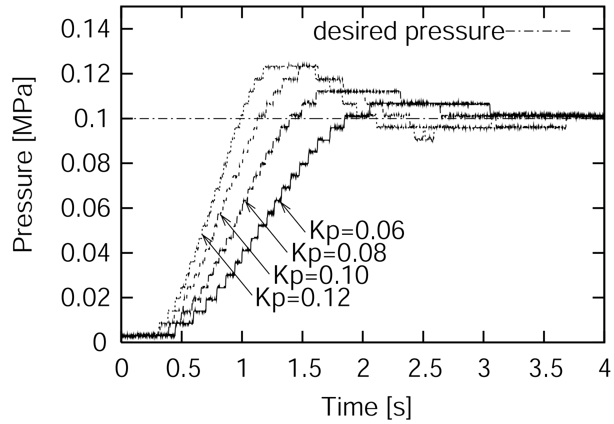


Fig. 7. Transient response in proportional control of pressure

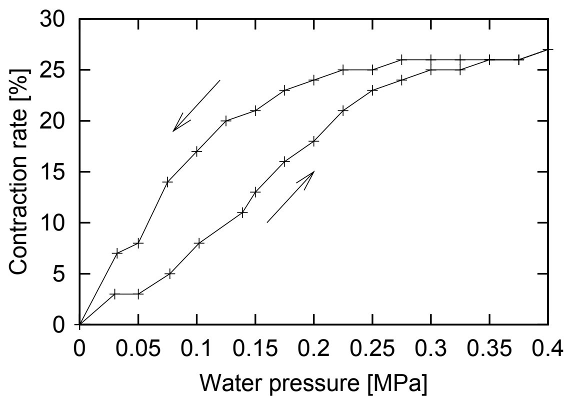


Fig. 6. A McKibben actuator driven by water flow

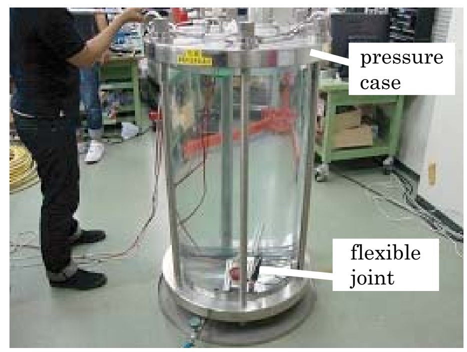


Fig. 8. Pressure case

one actuator driven by air flow (see Figure 4 and 6) due to the difference in compressibility between water and air. Figure 6 shows the contraction rate of the actuator driven by the series coupling pump. This resulted in contractions of 20% of its natural length at 0.25 MPa, regardless of the hysteresis loop of the McKibben actuator. Figure 7 shows that the transient response of the pump was proportional to the desired pressure, indicating a second order response. The symbol K_p in this figure is the feedback gain of the proportional control. Using this series-coupling pump, we could control the pressure to drive the McKibben actuator. In addition, the flow rate of this bilge pump at no load was 50.4 L/min, which was high enough to drive the actuator in real-time.

C. Performance of the pump in a high pressure environment

In this section, we confirm the performance of the pump in a high-pressure environment (Figure 8). We equipped the flexible joint with two strain gauges to measure the deformation of the joint in a high-pressure environment. We estimated the deformation of the joint from the differential voltages of the two gauges. Figure 9 shows the deformation volume of the joint in response to pressure. The vertical axis shows the output voltage, with a higher voltage indicating greater deformation of the joint. Under 0.1 MPa pressure environments, there were no differences in the performance of the joint. Figure 10 shows the deformation volume of the joint under 1.0 MPa pressure environments. We applied an input voltage of 24 V to the pumps. We observed no differences between the pumps under 0.7 MPa pressure environments, indicating that this pump can be used under 0.7 MPa pressure environments. We also confirmed that the outer case of the pumps deformed above 0.8 Mpa pressure environments. Reinforced outer cases may allow these pumps to perform at higher pressure.

D. Flexible joint

We found that the range of moving angles of the joint was dependent on the characteristics of the flexible joints. We utilized leaf springs made of carbon tool steel (Young's modulus; 206 GPa) as flexible joints in the mechanism shown in Figure 11. The rigid parts of the link were made of polymer foams, which have a density of about 0.2, much lower than that of water 1.0. We need to design the joint mechanism to neutral buoyancy. The symbols l, t, w represent the length, thickness, and width of the leaf springs between two rigid parts. Both ends of the actuator are arranged on the rigid parts as shown in this figure. A screw was used to fix each end point so that the translational position could not

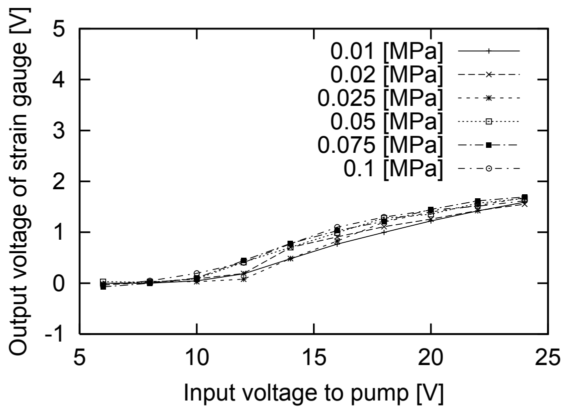


Fig. 9. Deformation volume of the joint in pressure case

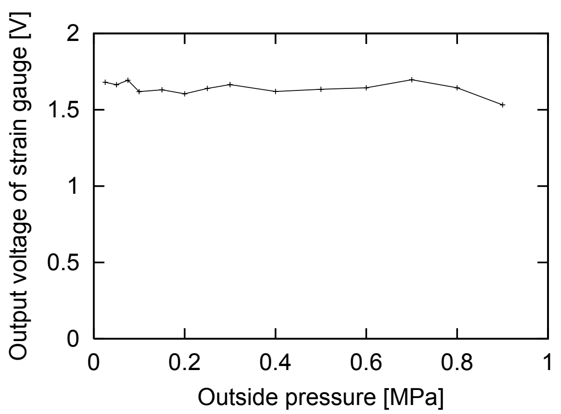


Fig. 10. Deformation volume of the joint under 1.0 MPa pressure

change, but the angle was able to rotate. The width w of the leaf spring was set to 20 mm. The length d between the leaf spring and the fixed point of the actuator was 10 mm. The momentum generated by the actuator would be larger at greater length d, but the range of movement would be smaller because the contraction length would be constant if the same McKibben actuator were applied. If symbol θ is the tip angle of the link, or the relative angle between two rigid parts during contraction of the McKibben actuator, then the angle θ of the link will change for characteristics of flexible parts. The length l can be set to 25 mm (Figure 12-(a)) or 30 mm (Figure 12-(b)), at each of which we compared the differences of the angle θ relative to thickness w. Our findings showed that thicker flexible parts would straighten the range of moving angles of the link. In addition, the angles had little influence on the thickness t (See Table I, showing tip angles at 0.28 MPa pressure). The spring constant k for the bending of a leaf spring can be calculated using material mechanics as;

$$k = \frac{Ewt^3}{4l^3}, \tag{1}$$

where E is Young's modulus. This equation showed that the spring constant k is proportional to t^3 and $1/l^3$. The

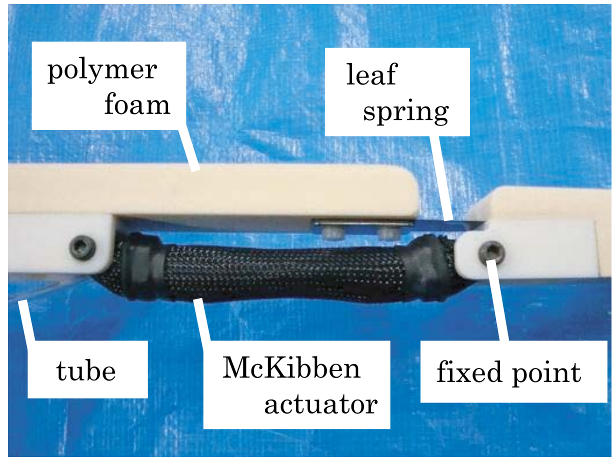


Fig. 11. Overview of a flexible Joint

TABLE I

ANGLE OF THE LINK AT 0.28 MPA

l [mm]	t [mm]	θ [deg]
25	0.3	67
25	0.4	56
30	0.2	70
30	0.3	65
30	0.4	53

rate of change of thickness t was larger than that of length l, resulting in differences in the range of tip angles. During contractions, the McKibben actuator applies an external force by restoring the leaf spring. Since the contracting length of the McKibben actuator depends on the load, the magnitude of change in the tip angle was not linear to variations in properties.

IV. EXPERIMENT

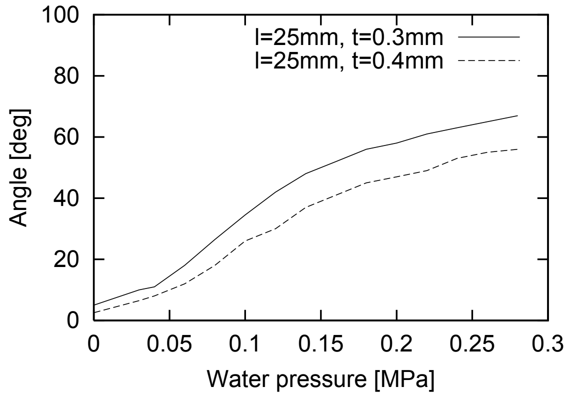
We have also confirmed the availability of the joint mechanism experimentally. The joint mechanism can be applied to a master-slave system with three joints driven under water.

A. Prototype of multi-jointed arm

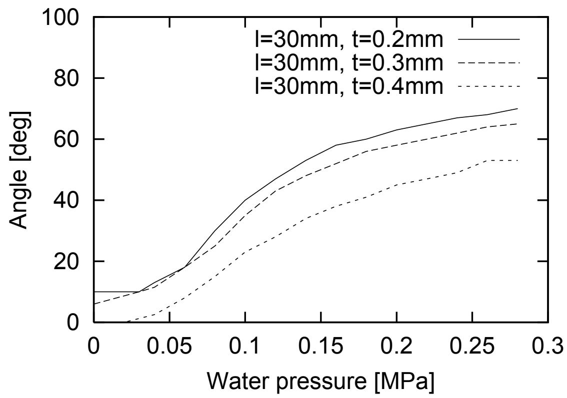
We developed a multi-jointed arm consisting of three flexible joints (Figure 13), such that this arm has three degrees of freedom (DOF). The three joints correspond to the two DOF of a human shoulder and the one DOF of a human elbow. We applied a leaf spring (length l; 10mm, thickness t; 0.3mm, width w; 20 mm) as the flexible joint. If θ_1, θ_2, and θ_3 are the angles of the i-th joint, respectively (Figure 13), the entire length of the arm is 770 mm and its total weight in air is 330 g. In addition, the generative force at the tip of the arm was been measured about 700 gf. This generative force is the natural state of the arm, with each of the angles θ_1, θ_2, and θ_3 being zero degrees. We confirmed that this prototype could be driven, even under water (Figure 14).

B. Master-Slave system

We applied a parallel link mechanism mounted on a rotational stage to drive the slave arm (Figure 15). This



(a) at length l = 25mm



(b) at length l = 30mm

Fig. 12. Tip angle during contraction of a McKibben actuator

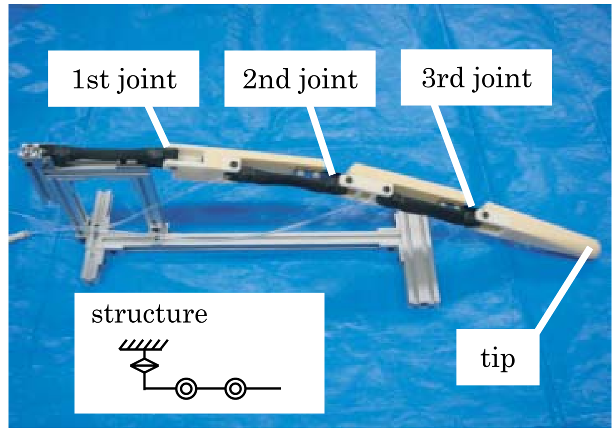


Fig. 13. Slave arm including a flexible joint driven by water pressure

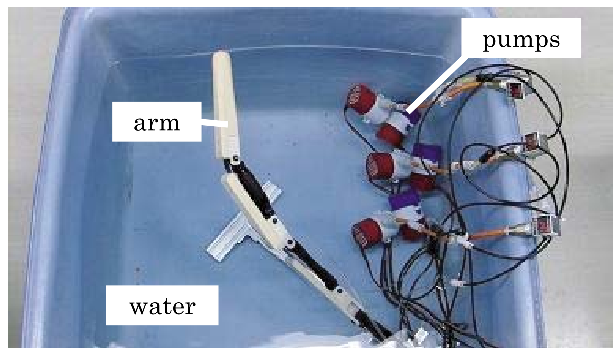


Fig. 14. Experimental setup for under water

parallel link mechanism has two degrees of freedom in planar motion. The angle of the rotational stage corresponds to the first joint of the slave system, with the angles of the parallel link corresponding to the second and third joints, respectively, of the slave system. An encoder was used to measure each angle. The control law was based on a proportional signal for a desired pressure of the water pump. The next input voltage $\boldsymbol{u}$ of the master-slave system could be calculated from the current input $\boldsymbol{u}^{'}$ using the equation:

$$\boldsymbol{u} = \boldsymbol{K}_p(\boldsymbol{P}_d - \boldsymbol{P}) + \boldsymbol{u}^{'}, \tag{2}$$

where $\boldsymbol{K}_p$, $\boldsymbol{P}_d$, $\boldsymbol{P}$ are the gain matrices, desired pressure, and current pressure, respectively. Current pressures were measured by pressure meters (GC31, Nagano Keiki Co. Ltd., Japan). The pressure obtained by the sensor converts the tip angle of the joint based on the results measured in Figure 12. Figure 16 shows an estimation of the angle, using a third degree equation. Figure 17 shows successive images obtained during the master-slave motion. In Figure 17-(a), (b), and (c), the master arm mainly drives the first, second, and third joints, respectively, of the slave arm, whereas, in Figure 17-(d), the master arm drives all 3 joints of the slave arm simultaneously. These findings confirm that the arm can be successfully operated, including flexible joints driven by water pressure.

V. Summary

We have described here a joint mechanism for underwater robots with manipulators, focusing on prototyping and controlling of the joint mechanism. This mechanism restores the arm to its original state in response to deformation, allowing one prismatic actuator to adduct each joint. The joint is also flexible, allowing the arm to avoid contact with an unplanned environment. We utilized a leaf spring as the flexible joint and a McKibben actuator driven by water pressure as the prismatic actuator and developed a water pump connecting two bilge pumps in series to drive the McKibben actuator under water. We then discussed the characteristics of the proposed joint mechanism in terms of the thickness and the length of the flexible joint. Finally, we showed experimentally that the prototype of a master-slave system with the joint mechanisms could be driven successfully. In future, we intend to examine what happens when the arm contacts unplanned objects and environments. We experimentally estimated the angle of an arm including the joint mechanism through experimental results, but the precision of these estimates may worsen during contact

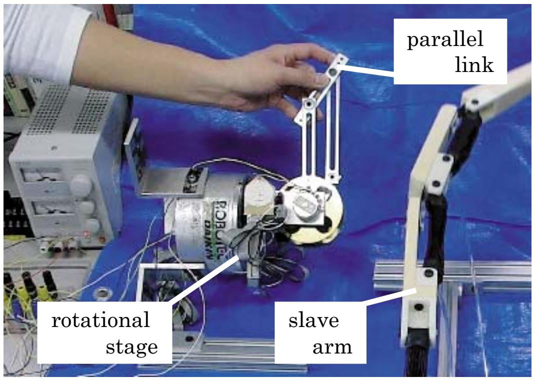


Fig. 15. Master arm

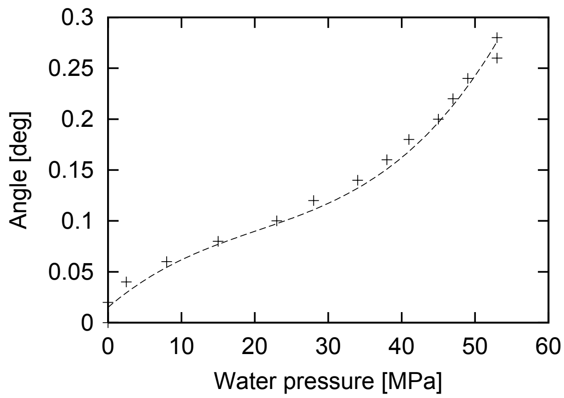


Fig. 16. Estimation of joint angle during contractions

because of the external force and geometrical constraints. In these cases, visual feedback signaling should compensate the tip position of the arm. We will apply passive elements with variable mechanical impedances, especially damping properties, to improve its performance [21].

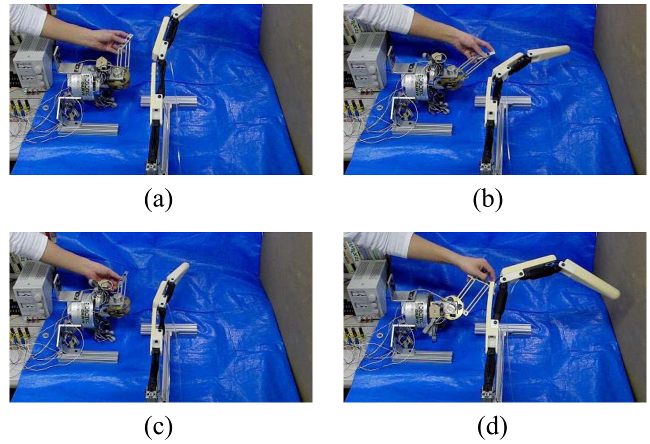


Fig. 17. Operation of an arm with flexible joints driven by water pressure using a Master-slave system

REFERENCES

[1] T. J. Tarn, G. A. Shoults, and S. P. Yang, ”A Dynamic Model of an Underwater Vehicle with a Robotic Manipulator using Kane’s Method”, Autonomous Robots, Vol. 3, pp.269-283, 1996.

[2] G. Antonelli, F. Caccavale, S. Chiaverini, and L. Villani: ”Tracking control for underwater vehicle-manipulator systems with velocity estimation”, IEEE Journal of Oceanic Engineering, Vol. 25, Issue 3, pp.399-413, 2000.

[3] C. Canudas-de-Wit, E. O. Diaz and M. Perrier: ”Nonlinear Control of an Underwater Vehicle/Manipulator with Composite Dynamics”, IEEE Transactions on Control Systems Technology, Vol. 8, No. 6, 948-960, 2000.

[4] K. N. Leabourne and S. M. Rock: ”Model development of an underwater manipulator for coordinated arm-vehicle control”, Proc. of OCEANS ’98 Conference, pp. 941-946, 1998.

[5] N. Sakagami, M. Inoue and S. Kawamura, ”Theoretical and Experimental Studies on Iterative Learning Control for Underwater Robots”, International Journal of Offshore and Polar Engineering, Vol.13, No.2, pp.120-127, 2003.

[6] T. I. Fossen: Guidance and Control of Ocean Vehicles, John Wiley & Sons Ltd, 1994.

[7] N. Sakagami, M. Shibata, S. Kawamura, T. Inoue, H. Onishi and S. Murakami, ”An Attitude Control System for Underwater Vehicle-Manipulator Systems”, Proc. IEEE Int. Conf. on Robotics and Automation, accepted!$2010.

[8] S. Alfayad, F. B. Ouezdou, F. Namoun and G. Cheng, ”Lightweight High Performance Integrated Actuator for Humanoid Robotic Applications: Modeling, Design & Realization”, Proc. pf the 2009 Int. Conf. on Robotics and Automation, pp.562-567, 2009.

[9] C. P. Chou, and B. Hannaford, ”Static and Dynamic Characteristics of McKibben Pneumatic Artificial Muscles”, Proc. IEEE Int. Conf. on Robotics and Automation, Vol.1, pp.281.286, 1994.

[10] S. Wakimoto, K. Suzumori, and T. Kanda, ”Development of intelligent McKibben actuator”, Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.487-492, 2005.

[11] M. Mori, K. Suzumori, S. Seita, M. Takahashi, T. Hosoya, and K. Kusumoto, ”Development of very high force hydraulic McKibben artificial muscle and its application to shape-adaptable power hand”, Proc. of the IEEE International Conference on Robotics and Biomimetics, pp.1457-1462, 2009.

[12] T. Noritsugu and T. Tanaka, ”Application of rubber artificial muscle manipulator as a rehabilitation robot” IEEE/ASME Transactions on Mechatronics, Vol. 2 , Iss. 4, pp. 259-267, 1997.

[13] J. M. Paros and L. Weisbord, ”How to design Flexure Hinges”, Machine Design, Vol. 37, pp.151-156, 1965.

[14] N. Lobontiu, ”Compliant Mechanisms: Design of Flexure Hinges”, CRC Press, 2003.

[15] H. Asakawa and T. Fukuma, ”Spurious-free cantilever excitation in liquid by piezoactuator with flexure drive mechanism”, Review of Scientific Instruments, Vol.80, 103703, 2009.

[16] F. Aral, D. Azuma, K. Narumi, Y. Yamanishi, and L. Yu-Ching, ”Design and fabrication of a shape memory alloy actuated exoskeletal microarm”, International Symposium on Micro-NanoMechatronics and Human Science, pp.339-343, 2007.

[17] N. Takesue, Z. Guoguang, J. Furusho, M. Sakaguchi, ”Precise position control of robot arms using a homogeneous ER fluid”, Control Systems Magazine, Vol. 19, Iss. 2, pp.55-61, 1999.

[18] T. Nakamura, N. Saga, M. Nakazawa and T. Kawamura, ”Development of a Soft Manipulator Using a Smart Flexible Joint for Safe Contact with Humans”, Proc. of the 2003 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics, pp.441-446, 2003.

[19] M. Shibata, T. Yoshimura, and S. Hirai!$”Angle Control of Loosely Coupled Mechanism in 3D Space Using Length Sensors”!$Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, pp.1178-1183, 2007.

[20] T. Yoshimura, M. Shibata, and S. Hirai!$”Stochastic Static Analysis of Link Driven by Actuator Bundles”!$Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems!$pp.5685-5690!$2009.

[21] S. Kawamura, T. Yamamoto, D. Ishida, T. Ogata, Y. Nakayama, O. Tabata, and S. Sugiyama, ”Development of Passive Elements with Variable Mechanical Impedance for Wearable Robots”, Proc. of International Conference on Robotics and Automation, pp.248-253, 2002.