

An Intelligent Cooperative Control for Nonlinear Actuators

Mikio YAMAZAKI and Seiji YASUNOBU
University of Tsukuba

Tennodai, Tsukuba, 305-8573 Ibaraki, JAPAN
E-mail: yamazaki_ics@edu.esys.tsukuba.ac.jp

Abstract—Soft actuators are expected to be applied for human assistive devices by making multiple actuators cooperate. However, it is difficult to cooperative control them using conventional linear controllers because soft actuators have nonlinear characteristics. On the other hand, humans are able to control own muscle which is nonlinear actuator and work together. In this paper, an intelligent cooperative controller that controls cooperative movement of multiple nonlinear actuators is proposed. The controller was constructed referring to a human’s cooperative work, and consists of multiple control parts, each control part handles each actuator. The effectiveness of the proposed controller was confirmed experimentally using a pneumatic lift device.

I. INTRODUCTION

Soft actuators that have a non-rigid mechanism attracts attention as an actuator used for the human assistive device in the medical treatment and welfare fields. Because a soft actuator have a flexible structure, it is possible to use it close to human.

When the soft actuator is applied to the human assistive device, it is necessary to compose the device by using multiple soft actuators to increase degree of freedom and to control soft actuators simultaneously. However, multiple soft actuators are difficult to cooperative control using conventional linear controller because the soft actuator is a nonlinear actuator that has a complex input-output characteristic.

On the other hand, human can do the cooperative activity by controlling the muscles that are nonlinear actuators. Human moves to be match for other party’s movement and people can work cooperatively.

In this paper, an intelligent cooperative controller is proposed, which controls cooperative movement of multiple nonlinear actuators. Nonlinear actuators are controlled to moving cooperate referring to human’s cooperative activity. As a soft actuator, McKibben Pneumatic Muscle (PM) driven by using compressed air is used. PM is flexible and has a high power/weight ratio. Moreover, the PM is safer when compared to electric and hydraulic actuators even in the event of a malfunction. Therefore, the PM has been used in human assistive devices and other such device [1][2]. The proposed intelligent cooperative controller is applied to a pneumatic lift device using two PMs and the effectiveness of the controller is confirmed.

II. INTELLIGENT COOPERATIVE CONTROL

A. Human’s cooperative work

To construct intelligent cooperative controller for multiple nonlinear actuators, human’s cooperative work is considered. When human works alone, you can work by considering only about own movement. However, when multiple human work together, it is necessary to consider not only own movement but also other party’s movement, and to do the cooperating movement. To consider other party’s movement, human takes communications (talking and gesture, and so on) with the other party and expects the other party’s idea and next movement. And, human decides the own movement that achieve the work purpose and cooperative movement with other party’s movement. Like this, human achieves the cooperative work by considering multiple elements.

As an example, a cooperative work to lift luggage up to a target height by two people is shown in figure 1. When human lifts luggage alone, you only has to consider the speed that he lifts and the difference between a present height and a target height. However, when two people lift luggage, it is necessary to consider not only the own movement but also the speed that the other party lifts and the inclination of luggage. Human decides own next movement that cooperate in the other party’s movement in considering of the own force and the information transmitted from the other party. Then, human transmits it to the other party. The other party decides his own movement from the transmitted information and the his own force. Thus, human has been achieving cooperative work in consideration of multiple elements that include the other party’s movement.

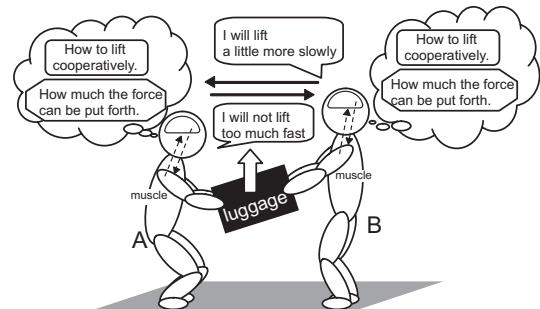


Fig. 1. Human’s cooperative work

B. Intelligent cooperative controller

A schematic of the proposed intelligent cooperative controller is shown in Fig. 2. The controller is constructed emulating human's cooperative work. The controlled object by the proposed intelligent controller is a device that has multiple nonlinear actuators. The intelligent cooperative controller consists of multiple control parts, each control part control each actuator. As for each control part, a control instruction inputs to an actuator, and an output and a state of the actuator are received. To do the cooperative movement, each control part exchanges information of the actuator that of each one controls. Information exchanged are "present state" that is measured "future state" that is calculated in each control part. The control part is built in the model of the controlled object and the control rule, and decides the control instruction by predictive fuzzy control [4].

The control part describes human control methodology using the if-then rule. For example

DO(control instruction U is \hat{U}_k)
 IF(control instruction U is $\hat{U}_k \rightarrow \hat{x}_{own}$ is good AND the relation between \hat{x}_{own} and \hat{x}_{other} is good

where: \hat{x}_{own} is the future state of the controlled actuator calculated with the model when U is \hat{U}_k , \hat{x}_{other} is the future state of the other actuator transmitted from the other controller.

The control part decides the control instruction by the following process. Firstly, a candidate control instruction is assumed and the future state is calculated using the model of the controlled object. Next, a fuzzy multipurpose evaluation is done using a membership function and the control rule with the maximum evaluation value is determined. Finally, the calculated value based on this control rule is output as a control instruction. The inference process is described in chapter III-B.

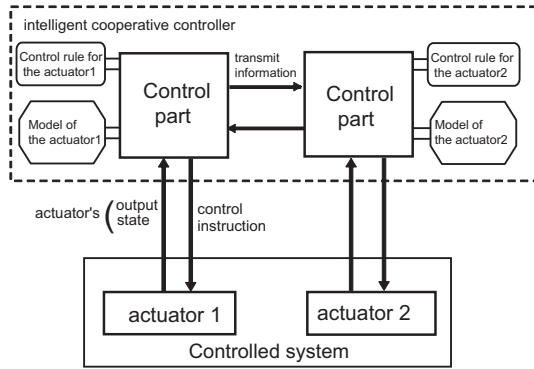


Fig. 2. Composition of the intelligent cooperative controller

III. INTELLIGENT COOPERATIVE CONTROL OF THE PNEUMATIC LIFT DEVICE

A. The pneumatic lift device

A pneumatic life device was manufactured in order to serve as a controlled object. This device, which lifts a seat, incorporates two McKibben Pneumatic Muscles (PMs) arranged in

parallel. The layout of pneumatic lift device is shown in Fig. 3. The pneumatic lift device assumes a human assistive device that assists older person to take a bath and ascend and descend to the bed by lifting the seat using two PMs. To lift the seat horizontally, it is necessary to match the contraction of the right and left PMs. The pneumatic lift device is measured lengths, inner air pressures and contraction forces of the PMs, and controlled by a control instruction input to an electro-pneumatic regulator.

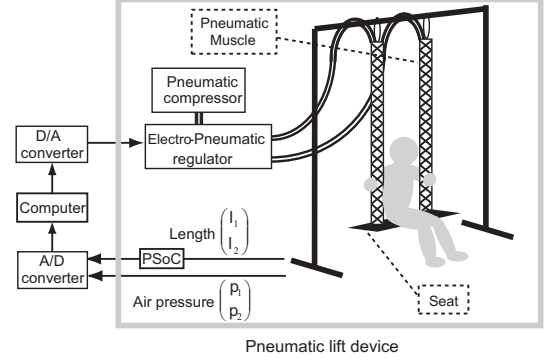


Fig. 3. Composition of the pneumatic lift device

The forward model of the PM shows the input-output characteristic with the air pressure being the input and the contractive force being the output. The forward model is obtained by finding the relation between the length, air pressure and contractive force of the PM. This relation was determined by hanging a weight on the bottom of the PM and then varying the weight and air pressure. The relationship resulting from these measurements is shown in Fig. 4. The PM exhibits hysteresis due to coulomb friction [6]. Thus, the PM has different lengths depending on whether it is expanding or contracting. Here, an average value is taken.

The relation between f and $l_0(p) - l$ is shown in Fig. 5, where l is the length of the PM, p is the air. From Fig. 5, f and $l_0(p) - l$ are proportional for air pressures of 0.15MPa or more. Thus, the PM may be assumed to be a spring element for which the spring constant changes according with air pressure. Therefore, the contractive force f may be described as follows

$$f = K(p)(l - l_0(p)) + \hat{C} \quad (1)$$

where: $K(p)$ is the spring constant for the air pressure p , \hat{C} is the coulomb frictional force of the PM.

Denoting the length of the PM as L , the forward model of the PM can be written

$$f = \hat{P}_L(p, \hat{C}) = \hat{C} + K(p)(L - l_0(p)). \quad (2)$$

B. Intelligent cooperative controller

The intelligent cooperative controller of the pneumatic lift device was composed (Fig. 6). This intelligent cooperative controller consists of two control parts that control right and left PMs. Each control part exchanges an information about a

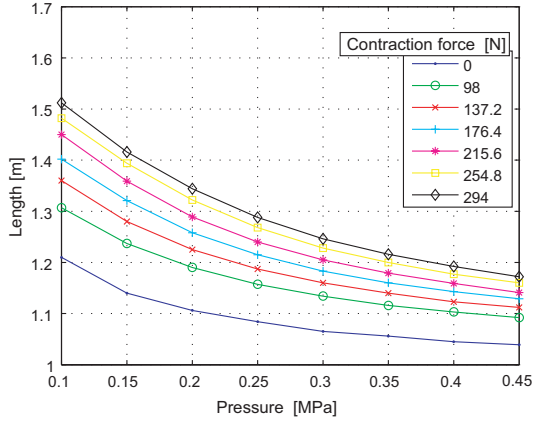


Fig. 4. Relationship between the length, air pressure and contractive force of the PM

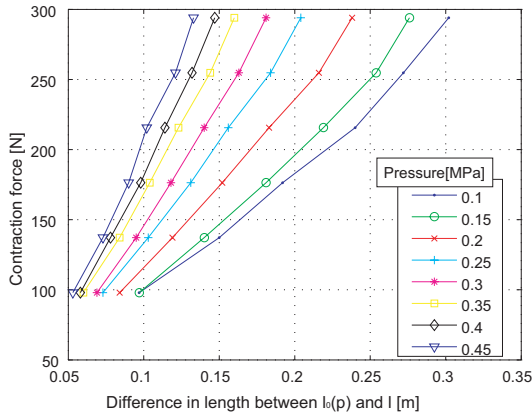


Fig. 5. Relation between f and $l_0(p) - l$

future state of a PM that of each controls. The future state of the PM is obtained during the decision of the control instruction that uses predictive fuzzy control. Each control part has a model of a PM and a control rule.

Because the PM has a state-dependent input-output characteristic, the model of the PM is determined in real time from the its present state [3].

The control rule describes human control methodology using the if-then rule. When lifting a seat horizontally up to the target height by two people, human considers multiple elements as follow,

- Difference between the present lifted height and the target lifted height
- Lifted speed
- Difference between the own lifted height and the other party's lifted height.

Human decides a next movement in consideration of these multiple elements. The control rule is described referring to such human's decision like DO (control instruction U is \hat{U}_k)IF (control instruction U is $\hat{U}_k \rightarrow$ the error between \hat{l}_k and the target position l_t is small)

where: \hat{l}_k is the future length of the PM calculated with the model of the PM when U is \hat{U}_k .

The control rule is shown as follows

- Do U is U_{old}
if (U is $U_{old} \rightarrow e$ is “Good” and $cooe$ is “Good”).
- Do U is $U_{old} + 1.0$
if (U is $U_{old} + 1.0 \rightarrow e$ is “Very Good” and $cooe$ is “Very Good”).
- Do U is $e_{now} * kp + \dot{e}_{now} * kd$
if (U is $e_{now} * kp + \dot{e}_{now} * kd \rightarrow e$ is “Very Good” and $cooe$ is “Very Good”).

In the control rule, U_{old} is the last control instruction, e is the error between the presumed length of the PM (\hat{l}) and the target length (l_t) and $cooe$ the error between the presumed length of the PM (\hat{l}) and the presumed length of the other PM. The presumed length of the other PM is transmitted from the other control part.

The inference process of the control part based on the model of the PM and the control rule is shown in Fig. 8. Firstly, a candidate control instruction is assumed and the future length is calculated using the model of the PM. Next, a fuzzy multipurpose evaluation is done using membership functions. The membership functions for evaluation are shown in Fig. 7. Finally, the control rule with the maximum evaluation value is determined and the calculated value based on this control rule is output as a control instruction.

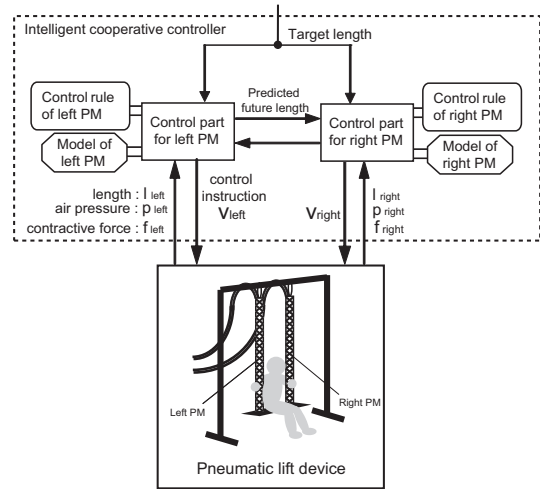


Fig. 6. Composition of the intelligent cooperative controller of the pneumatic lift device

IV. EXPERIMENT

To confirm the effectiveness of the proposed intelligent cooperative controller, experiments were performed on a pneumatic lift system. An overview of the device is shown in Fig. 9. Two experiments on “level control experiment” and “lift control experiment” are conducted.

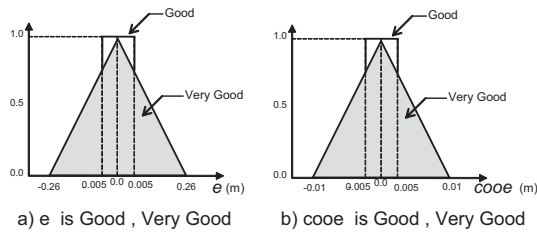


Fig. 7. Membership functions used to evaluate purposes

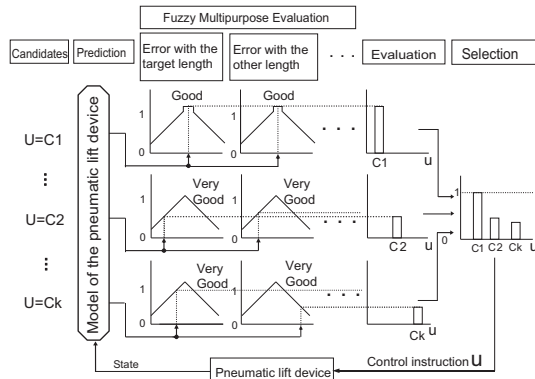


Fig. 8. Inference process of the control part

A. Level control experiment

In the level control experiment, the objective is only to keep the seat level without the target length. That is, the lift device is controlled so that the lengths of right and left PMs become the same. In this experiment, because only reducing the difference of the lengths of right and left PMs becomes a purpose, the membership function used for the evaluation by the predictive fuzzy control is the function concerning “Difference of a right and left PMs”. The level control experiment is conducted by changing the load of one of the PM when the seat is a horizontal state. When not controlling, the length of the PM changed the load changes and the seat inclines. It is confirmed whether the seat can be kept the horizontal by using intelligent cooperative controller. The initial PM lengths were 1.3 [m] and the initial loads were 5 [kg] for both the right and left PMs. The load of 10 [kg] is added to the right PM.

Contractive forces of the right and left PMs are shown in Fig. 10, and the results using the intelligent cooperative controller are shown in Fig. 11. The results without controlling are shown in Fig. 12 for the comparison. Because the load is added to the right PM at 4 seconds, the contractive force of the right PM has been changed. And, the length of the right PM becomes long at the same time. By using the intelligent cooperative controller, the right and left PMs are controlled so that lengths of two PMs become the same.

From the above-mentioned result, it was confirmed to be able to keep the seat level by matching the length of the right and left PMs by the proposed controller.



Fig. 9. Overview of the pneumatic lift device

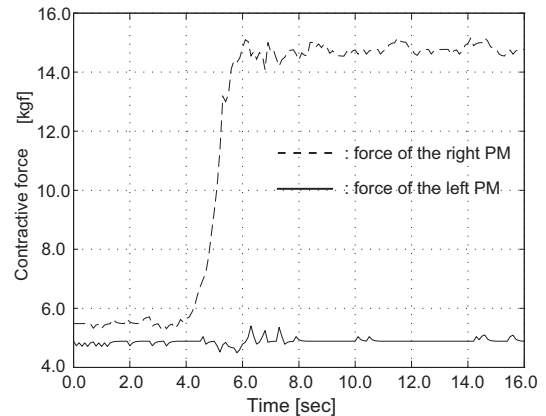


Fig. 10. Contractive force of the PMs

B. Lift control experiment

In the lift control experiment, the objective is to lift the seat to a target length quickly and without an overshoot, in addition to keep the seat level. Both of the PMs of the pneumatic lift device are simultaneously contracted to a target length. To lift the seat horizontally, it is necessary to match the contraction of the right and left PMs.

In this experiment, the membership function used for the evaluation by the predictive fuzzy control is the functions concerning “Difference of the length of right and left PMs” and “Difference between present lengths and target lengths of the PMs”.

The lift control experiment is conducted by contracting the

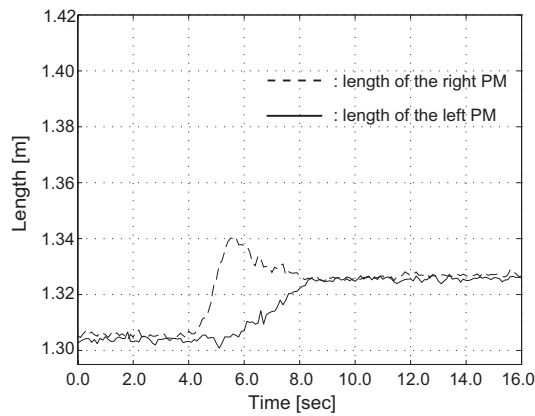


Fig. 11. Length of the PMs (Intelligent cooperative controller)

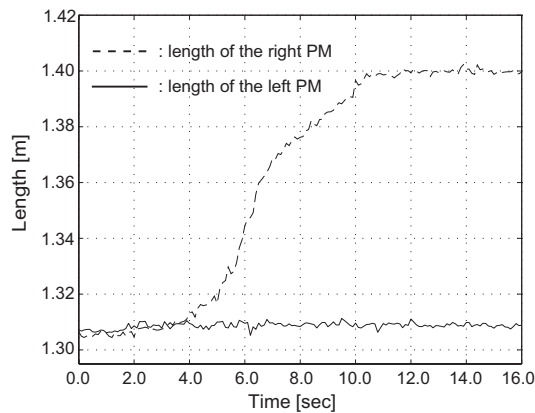


Fig. 12. Length of the PMs (Without controlling)

two PMs when the right and left loads are different. It is confirmed whether the seat can be kept the horizontal and lifted to the target length. The initial PM length was 1.60 [m], the target length was 1.35 [m], the load was 10 [kg] for the right PM and 20 [kg] for the left PM. The experiment was performed using three control methods: PD controller added gravity compensation, intelligent cooperative controller (without level evaluation), and intelligent cooperative controller (with level evaluation).

1) *pd controller added gravity compensation*: The results using the PD controller are shown in Fig. 13. The proportional gains (kp) and derivative gains (kd) assumed were $kp=9.2$ and $kd=11.3$ for the right PM and $kp=5.5$ and $kd=7.8$ for the left PM. It took about 3.0, 3.3 seconds to reach the target length and the seat does not remain level during the lifting process.

2) *intelligent cooperative controller (without level evaluation)*: The results using the intelligent cooperative controller without level evaluation are shown in Fig. 14. This controller uses the membership function concerning “Difference between present lengths and target lengths of the PMs”. It took about 1.8, 2.2 seconds to reach the target length. Because the right and left PMs are independently controlled, the balance of contraction is poor. That is to say, the seat does not remain

level during the lifting process.

3) *intelligent cooperative controller (with level evaluation)*: The results using the intelligent cooperative controller with level evaluation are shown in Fig. 15. This controller uses the membership function concerning “Difference between present lengths and target lengths of the PMs” and “Difference of the length of right and left PMs”. The contraction of each PM is controlled in consideration of the future state of the other PM. Therefore, the balance of contraction improves between the right and left PMs, and the seat is lifted horizontally.

From the above-mentioned result, it was confirmed that the seat can be kept the horizontal and lifted to the target length when using the proposed intelligent cooperative controller.

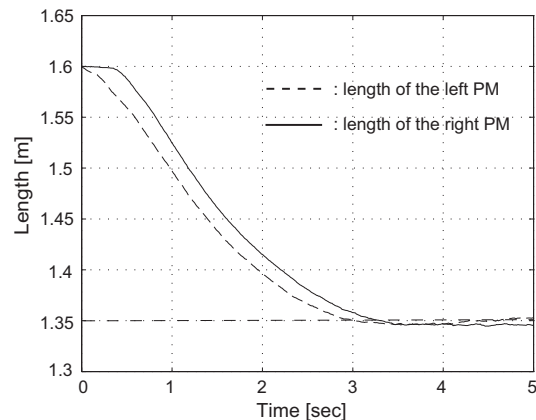


Fig. 13. Length of the PMs (pd controller added gravity compensation)

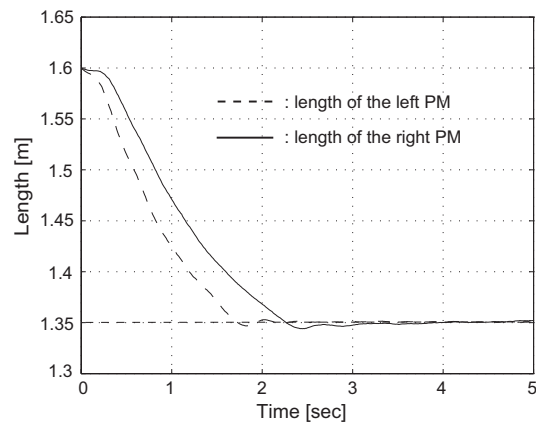


Fig. 14. Length of the PMs (intelligent cooperative controller “without level evaluation”)

V. CONCLUSIONS

In this paper, an intelligent cooperative controller was constructed for the cooperative movement of multiple nonlinear actuators. An intelligent cooperative controller consists of multiple control parts, each control part control each actuator. The intelligent cooperative controller decides a control instruction in consideration of multiple purposes including

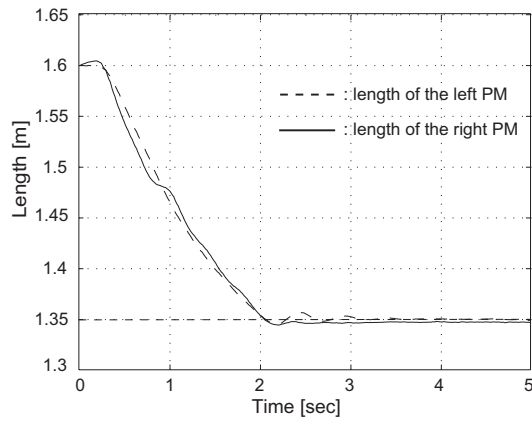


Fig. 15. Length of the PMs (intelligent cooperative controller “with level evaluation”)

the cooperation of multiple actuators like humans cooperative work.

This intelligent cooperative controller was applied to a pneumatic lift device using McKibben Pneumatic Muscles (PM) and was then subjected to experimentation. The experimental result confirmed that it was possible to control a cooperative contraction of the two PMs using this intelligent controller. Therefore, it has also been shown that the proposed intelligent cooperative controller is effective in controlling a cooperative movement of the multiple nonlinear actuators.

REFERENCES

- [1] T. Noritsugu and L. Gao, “Development of Wearable Waist Power Assist Device Using Curved Pneumatic Artificial Rubber Muscle”, *Journal of the Japan Fluid Power System Society*, Vol. 36, No. 6, pp. 143-151, 2005.
- [2] H. Kobayashi, Y. Ishida, T. Matsushita and M. Koseki, “Development on Muscle Suits to Make Disable People Move” , *Technical report of IEICE. HCS*, Vol. 25, No. 52, pp. 55-61, 2001.
- [3] M. YAMAZAKI and S.YASUNOBU, “An Intelligent Control for State-Dependent Nonlinear Actuator and Its Application to Pneumatic Servo System”, *SICE Annual Conference 2007*, pp. 2194-2199, 2007.
- [4] S. Yasunobu and S. Miyamoto, “Automatic Train Operation System by Predictive Fuzzy Control”, *Industrial Application of Fuzzy Control (M. Sugeno, Ed.)*, North Holland, pp. 1-18, 1985.
- [5] B. Tondu and P. Lopez “Modeling and Control of McKibben Artificial Muscle Robot Actuators”, *IEEE Control Systems Magazine*, Vol. 20, No. 2, pp. 15-38, 2000.
- [6] C. P. Chou and B. Hannaford “Measurement and Modeling of McKibben Pneumatic Artificial Muscles”, *IEEE Transactions on Robotics and Automation*, vol. 12, pp. 90-102, 1996.