Development of a Decoupling Wire Driven Exoskeletal Microarm for Endoscopic Submucosal Dissection

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***Abstract*— Endoscopic Sub-mucosal Dissection (ESD) has the low operability problem during operation by using surgical tools with a simple mechanism. In this paper, newly developed an exoskeletal microarm is proposed. For enabling the surgical operation of cancer tissues during ESD, a gripper is attached to the microarm based on a wire decoupling design. The fabrication methods for the microarm by using an electrical discharge machining and a photolithography are also shown. By using this approach, the developed extra-thin 2-DOF microarm can insert to the endoscope channel with the diameter of 2.7 mm.**

I. INTRODUCTION

Endoscopic surgery is a well-established method in modern medicine [1]. In particular, Endoscopic Sub-mucosal Dissection (ESD) is well known for availability of 10 mm-level tumor excision [2]. In ESD, for removing cancer tissues, a doctor inserts an oral endoscope into a stomach, and performs surgical procedures by using small tools. Therefore, large incisions, like the ones needed in open surgery, are not required. This is a minimally invasive procedure to apply a quick recovery for patients.

However, the disadvantages of ESD are the narrow operative field provided by a single endoscope and the low operability by using a simple mechanism forceps. It uses a hook knife and an insulation-tipped electro-surgical knife (IT knife) to cut the lesion. IT knife is designed to prevent the penetration of the gastric wall by covering the tip of the electrical knife with a ceramic ball. However, perforation is still encountered, leading to prolonged resection time. Therefore, the ESD for gastric cancer requires an endoscopist with technical skills higher than those required for the other endoscopic procedures. A basic technical principle of the surgical resection is the resection of appropriate tissues, which is forced to stand-out by injecting saline under the tumor. However, this endoscopic surgery is “one-arm surgery” that it can only insert one endoscope to cut and exfoliate the lesion. Ideally, one arm is pulling the lesion and another arm to cut would improve the efficiency and reduce the risk of complications, such as bleeding and perforation from cutting the unconfirmed blood vessels. The exfoliating procedure with a hook/IT knife is especially difficult in the surgery. It takes the most of the surgery time. A couple of studies have attempted to address this issue. In clinical field, several techniques for assisting endoscopic surgery are proposed and conducted [3][4]. However, these approaches are not enough to solve the time-consuming and the skill-dependent problems on ESD, therefore, a new approach has been desired for years.

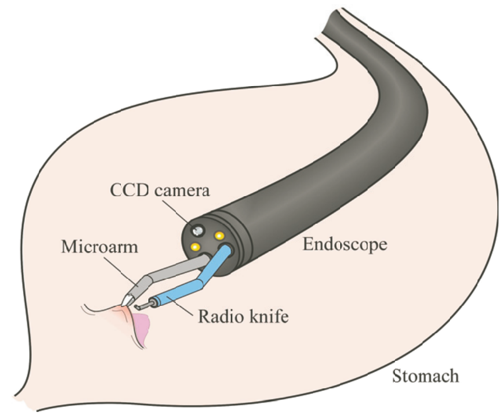

Fig. 1. Concept of micro-arm for ESD

Considering this background, we have proposed a surgical concept for ESD by utilizing a couple of microarms, as shown in Fig. 1 [5][6]. In this approach, a doctor can easily operate the surgical procedures without time-consuming manner by the wire driven microarms, which have multi-DOF for the wide-range movement. On the other hand, the conventional microarm has the coupling problem between the wire for the arm joint and the wire for the gripper, as shown in Fig. 2. When we open the gripper, the joint is also moved by the wire coupling. Therefore, we could not precisely control the movement of the microarm, and we may apply damage to tissue of organs by this problem. Furthermore, since the gripper was composed of the thin plates fabricated by photolithography technique, the grip force of gripper was not enough to lift up a tissue of organs.

In this paper, we newly propose the decoupling wire driven exoskeletal microarm with gripper enabling the surgical operation of a cancer in tissues during ESD. Based on both

This work has been supported by the Ministry of Education, Culture, Sports, Science and Technology Great-in-Aid for Scientific Research (21656064).

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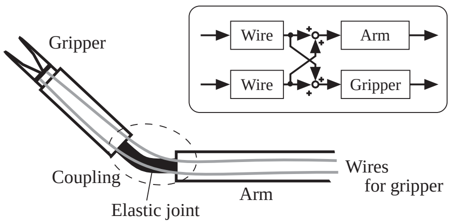


Fig. 2. Joint coupling problem of the conventional microarm

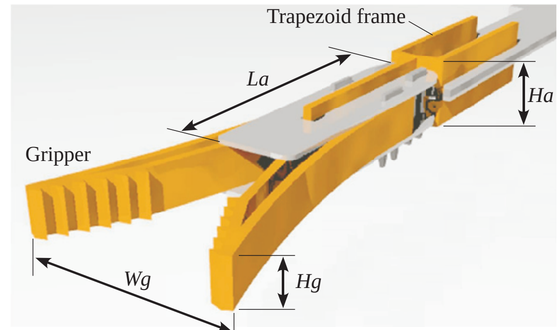
a photolithography and a wire-electric discharge technique, we develop the decoupling structure for the metal frame of the microarm. By using this approach, the developed extra-thin 2-DOF microarm can be inserted to the endoscope channel with the diameter of less than 3 mm. The developed microarm is capable of lifting up a tissue layer of organs during ESD. The remainder of this paper is organized as follows. In section II, we describe the related works with a robotic approach for surgical assist of minimally invasive surgery. In section III, we show the basic concept and decoupling design of the proposed microarm. We also show the fabrication method of the microarm by using an electrical discharge machining and a photolithography. In section IV, we describe the basic experiments that are essential to confirm the performance of the developed microarm with gripper. Finally, in section IV, we discuss the concluding remarks of the present study and our future plans.

II. Related Works

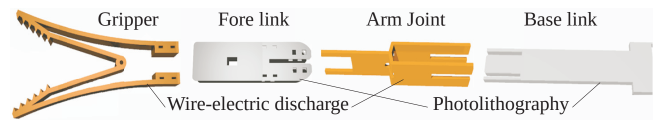
Microarms for endoscopic surgery: There have been many works discussing surgical assist microarms [7]. Catheter is a good tool for diagnosing inner surface of stomach, large intestine, and so forth [8][9]. Most catheters have a gripper, so that they can treat the surface of internal organs. However, when a catheter contacts to the stomach wall, it easily has deformation. It is difficult to keep the lifting posture of the catheter for surgical assist. Harada et al. [10] developed the 2-DOF micromanipulator with the diameter of 2.4 mm for intrauterine fetal surgery, even though it has no gripper. On the other hand, the robotic tools included endoscope system are developed by a couple of companies, for example EndoSAMURAI^{TM} (OLYMPUS CO. Ltd.) [11]–[13]. Since these robots are embedded in the specially-developed endoscope, we cannot apply these robots for a normal oral endoscope.

Decoupling mechanism: Most popular method for decoupling mechanism in robotics is composed of several gears. In this method, however, it is difficult to design a compact microarm for endoscope insertion. Ikuta et al. [14] have developed the 5-DOF wire driven microarm with the diameter of 3.0 mm for micro surgery in deep area of organs. In this device, a number of wires are required to control the microarm, even though the decoupled wire drive was achieved by the micro-joint design.

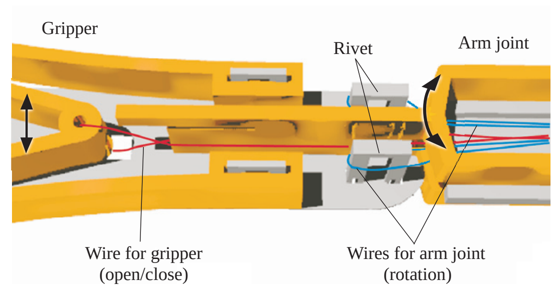
Based on the conventional works discussed above, we newly develop the specialized extra-thin microarm with a gripper for ESD.



(a) Overview of the microarm



(b) Mechanical parts



(c) Wire path and DOF

Fig. 3. Proposed microarm with gripper

III. Decoupling Wire Driven Exoskeletal Microarm

A. Concept

In actual ESD, the required specifications for a microarm mounted to an oral endoscope are as follows:

- Diameter of microarm: less than 3.0 mm
- Movable angle of microarm: ± 60–80 deg.
- Thickness of tissue layer to handle: 2.0–5.0 mm
- Weight of tissue layer to handle: approximately 30 g.

Fig. 3(a)–(c) shows a concept image of the proposed microarm which is composed of a base link, a fore link, an arm joint, and a gripper. Since the size limitation of endoscope channel is approximately 3.0 mm, we have to design the microarm with the diameter of less than 3.0 mm. To reduce the size of the microarm, we apply an exoskeletal structure for the arm design. The exoskeletal is well known for a miniaturized structure such as an insect arm. Moreover, since an exoskeletal structure has a rotational joint, we can estimate the exact posture of the microarm by measuring the joint angle from the outside of the body. In the conventional work, we have achieved the posture control of the exoskeletal microarm with one joint [5], even though the developed one has a wire coupling problem.

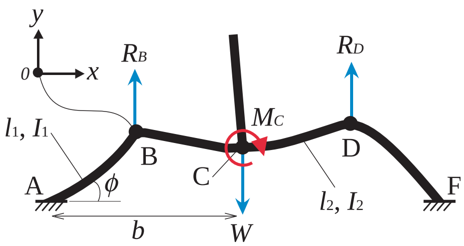


Fig. 4. Mechanical model for joint design

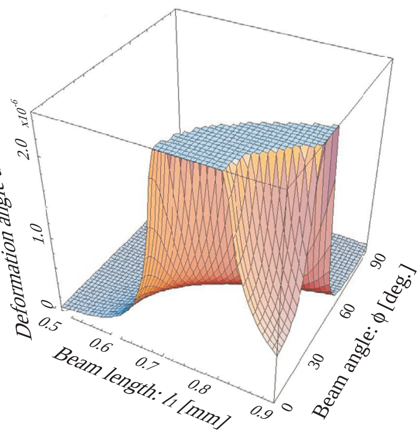


Fig. 5. Evaluation of the joint flexibility

At the first, based on an analytical approach, we design the arm joint for bending the microarm, and the gripper for grasping/lifting of stomach tissues. From these results, we also design the decoupling structure to assembling the mechanical elements of the microarm.

B. Arm Joint Design

Fig. 3(b) shows the basic structure of the arm joint, which has the shape of trapezoid frame. To increase the movable area of the arm joint, we actively apply the elastic deformation of the frame to the joint design.

Fig. 4 shows the trapezoid frame model for the arm joint where W, I_i, l_i, b, ϕ_b, M_C, R_B, and R_C are a tension by wire, a second moment of area, length of beams, a half length of bottom of trapezoid, angle from bottom of trapezoid, a moment at a point C, a normal force at point B, and a normal force at point D, respectively (i=1, 2). From this model, we calculate the appropriate parameters of l_i and ϕ for arm design. Here,

$$b = l_1 cos\phi + l_2. \tag{1}$$

Since the microarm has the size limitation, we use b=0.65 mm on this analysis. We can obtain the equation about the deformation of the beam BD as follows:

$$EI\frac{d^2y}{dx^2} = R_B x - M_C H(x - l_2) - W(x - l_2)H(x - l_2), \tag{2}$$

$$R_B = \frac{W(l_2 - d)}{2l_2}, \tag{3}$$

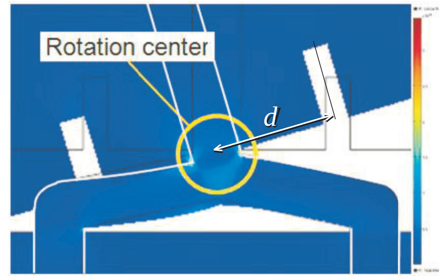


Fig. 6. Stress distribution of the designed joint

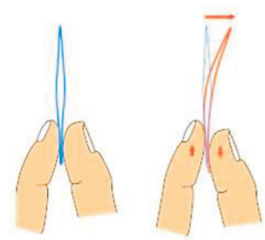


Fig. 7. Concept of the gripper design

where E, $H(x)$, and d are Young's modulus, Heaviside function, and a distance between the point C and the point of application of tensile force by wire as shown in Fig. 6, respectively. By using the equations (1)–(3), we simulate the deformation angle at C (see Appendix I), as shown in Fig. 5. For the simulation, we use W=1.0 N and d=0.8 mm. From this result, we determine the parameters such as l_1=0.67 mm, l_2=0.00 mm, and ϕ=12.0 deg.

To confirm the availability of the designed parameters, we carried out the FEM analysis by using the COMSOL Multiphysics software. Fig. 6 shows an example of the simulation result. From this figure, we can see that the rotation center exists in the center of the joint arm and the arm joint has large deformation by the wire tension. This means that we can realize the extra-thin microarm which has both the wire decoupling and the large movable angle of joint. The required accuracy of the designed parameters (50 μm order) is enough to fabricate the actual microarm by a wire-electric discharge machining.

C. Gripper Design

To implement a gripper to the microarm, it is important that gripper has a simple mechanism and a large grip force. From these points, we apply Muramatsu et al. [15] proposed principle which is based on a behavior of long pillar buckling (Fig. 7) to the gripper design. By utilizing this principle, we can develop the simple gripper without large mechanical elements. To determine the shape of the gripper, we carried out FEM analysis by the COMSOL Multiphysics software. As the result of trial and error, we decided the shape of the gripper which is normally-open type, as shown in Fig. 8. The appropriateness of shape design is confirmed through basic experiments, in section IV.

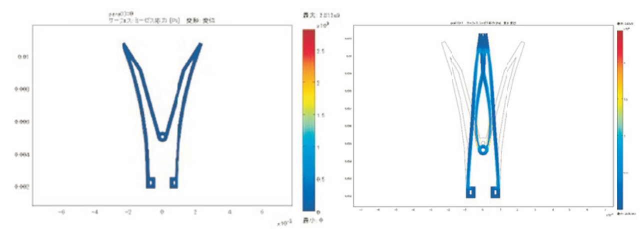


Fig. 8. Stress distribution of the designed gripper

(a) Joint (b) Gripper

Fig. 9. Elements of the microarm machined by electrical discharge machining

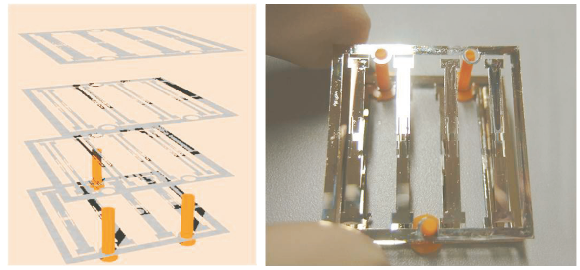


Fig. 10. Stacking Microassembly Process (STAMP)

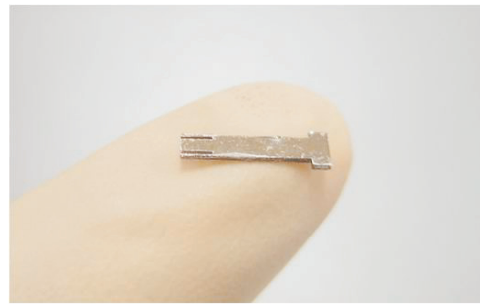


Fig. 11. Fabricated and assembled element for the microarm

D. Decoupling Design

From the discussed designs above, we describe the wire decoupling design for microarm and gripper. Fig. 3(c) shows the wire implemented microarm, where the red line shows the 1 wire for the gripper and the blue line shows the 2 wires for the arm joint. To achieve the wire decoupling, the wire for gripper is precisely passed through the center position of the arm joint. Therefore, even if the arm joint is bent by wires, the gripper is completely unaffected with the decoupling design. As a result of the design, we decide the parameters of the microarm such as the width of the opened gripper W_g=4.5 mm, the height of the gripper H_g=1.0 mm, the length of the fore link L_a=10.0 mm, and the height of the joint H_a=1.8 mm, respectively.

E. Fabrication

To increase the stiffness of the microarm, the arm joint and gripper were fabricated by using a wire-electric discharge, as shown in Fig. 9, where the material of each parts is phosphor bronze, and the thickness is 0.2 mm.

On the other hand, to assemble of the joint and gripper, we require the link parts with the accuracy of 10 μm order. By applying a photolithography to this fabrication, we develop the extra thin mechanical parts for the microarm [6]. At first, the sacrificial layer (LOR 5B, Tokyo Ohka Kogyo Co. Ltd.) is coated on Si wafer. Then Au-Cr is sputtered on the wafer (thickness=300 nm). Next, the photoresist (KMPR 3035, Kayaku Micro Chem Co. Ltd.) is coated on the substrate. After removing photoresist and sacrificial layer (Remover PG, Kayaku Micro Chem Co. Ltd.), ultrasonic cleaning is conducted to peel off the remaining Au layer.

Furthermore, by introducing the proposed Stacking Microassembly Process called STAMP [5] as shown in Fig. 10, we fabricate the layered link parts to increase the parts thickness. Fig. 11 shows the fabricated and assembled part (base link) for the microarm.

Finally, we complete developed the microarm with the diameter of 2.62 mm (maximum height: 1.9 mm, maximum width: 1.8 mm), which can insert the actual endoscope channel (2.7 mm), as shown in Fig. 12.

IV. Experiments

To confirm the performance of the developed microarm, we perform the basic experiments.

Effect of the decoupling design: The microarm was pulled by Bolfur wires (diameter=100 μm) with manual operation. Then, we measured the rotation angle of the microarm from the captured image by camera (Fig. 13(a)–(d)). From this experiment, we confirmed that the maximum rotation angle is 60 deg. with 27.0 N tension. Furthermore, we also confirmed that the arm joint movement is not mostly affected by that of the gripper, as shown in Fig. 14(a) and (b).

Grip force of the microarm: First, the grip force of the gripper was measured by the sensor made by a metal flat plate with a strain gauge. As a result, we confirmed that the grip force of the gripper is 0.52 N at a maximum. Next, a silicone rubber imitated a human tissue was gripped and lifted by the developed microarm, as shown in Fig. 15. In this experiment, we changed the thickness of the 100.0 x 50.0 mm size silicone rubber. From this experiments, it was confirmed that the microarm can lift up the rubber sheet with the thickness of 3.7 mm (21.0 g). In actual ESD, we have to handle a mucous membrane with a thickness of 2.0–5.0 mm and a weight of approximately 30 g. Therefore, based on the

Fig. 12. Developed microarm mounted with an endoscope

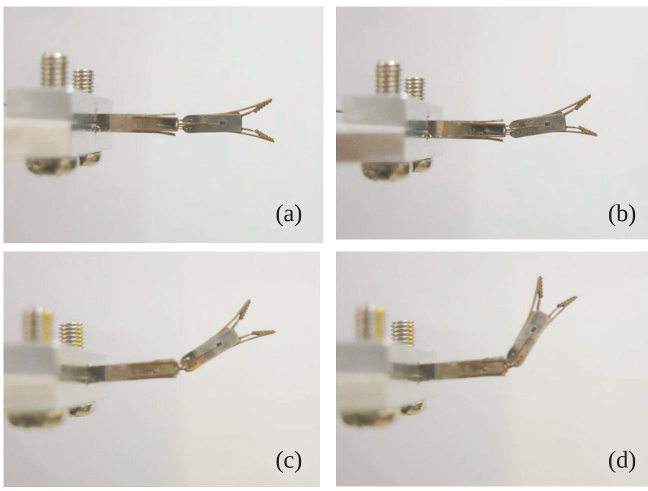


Fig. 13. Demonstration of the developed microarm

experimental results, we think that the developed microarm is great candidate for actual ESD.

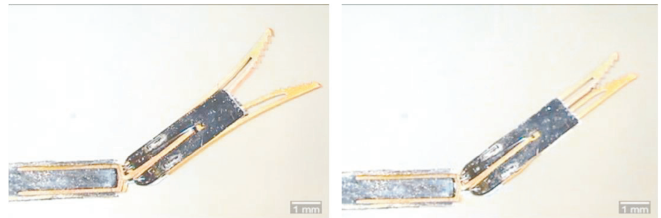
V. Future Works and Conclusions

A. Future Works

Since the limitation of the wire-electric discharge machining, the gripper cannot close perfectly, as shown in Fig. 14. Therefore, we think that the grip force of the microarm (0.52 N) is not enough to grasp the tissue without slipping during ESD. In the future work, we should redesign and fabricate the gripper to improve the grip force. The specific evaluation of the grip force will be conducted (e.g. the relationship between the gripper angle and the grip force).

On the other hand, the developed microarm was made from phosphor bronze and nickel which may cause allergic reaction. For a clinical application, the microarm should be coated by biocompatible material.

After developing of the microarm, we plan to control the microarm by using a motor drive. To control the posture of the arm joint, the microarm requires a rotation angle sensor, for example strain gauge. Furthermore, on the basis of the abovementioned experimental results, we are currently developing the wire driven system for animal experiment.



(a) (b)

Fig. 14. Decoupling effect of the developed microarm

Fig. 15. Overview of the lifting experiment

Through this experiment, the usability of the developed microarm is confirmed.

We believe that the developed microarm can be applied to other endoscopic surgeries, for example NOTES (natural orifice translumenal endoscopic surgery) [16][17].

B. Conclusions

Here, we described a newly developed decoupling wire driven exoskeletal microarm that can be applied to ESD. The main results of our study are as follows:

(1) The 1.8 mm thickness microarm is composed of a gripper with 0.52 N grip force, an arm joint with ± 60 deg. rotatable angle, and two link parts. These mechanical elements are fabricated by a wire-electric discharge and a photolithography technique.

(2) Through our basic experiments, we have confirmed the developed microarm can be installed to an endoscope channel with the diameter of the 2.7 mm and the wire decoupling of the microarm is achieved.

(3) Available handling size of the developed microarm is 100.0 x 50.0 x 3.7 mm (21.0 g), we can apply the microarm to actual tissue excision during ESD.

APPENDIX I
ANALYSIS FOR THE ARM JOINT

From equations (1)–(3), we can obtain the angle θ_c at point C as follows:

$$\begin{aligned}\theta_c &= \frac{dy}{dx}\\ &= \frac{1}{EI}\left[\frac{1}{2}R_B x^2 - M_C(x-l_2)H(x-l_2)\right]\\ &\quad -\frac{1}{EI}\left[\frac{W}{2}(x-l_2)^2 H(x-l_2)+c_1\right]. \qquad (4)\end{aligned}$$

From the equation (4), we can also obtain the deflection y_c at point C,

$$\begin{aligned}y_c &= \frac{1}{EI}\left[\frac{1}{6}R_B x^3 - \frac{M_C}{2}(x-l_2)^2 H(x-l_2)\right]\\ &\quad -\frac{1}{EI}\left[\frac{W}{6}(x-l_2)^3 H(x-l_2)+c_1 x + c_2\right], \qquad (5)\end{aligned}$$

where, c_i (i=1,2) is the constant value. When we suppose x=l_2 at point C, from the geometric condition,

$$\begin{aligned}y_c(l_2) &= \frac{1}{EI}\left[\frac{1}{6}R_B l_2^3 + c_1 l_2 + c_2\right]\\ &= \frac{-\delta_B\cos(\phi-\theta_B)+\delta_D\cos(\phi-\theta_D)}{2}, \qquad (6)\end{aligned}$$

where, δ_B, θ_B, δ_D, and θ_D are the displacement of the beam AB at point B, the angle of the beam AB at point B, the displacement of the beam DF at point D, and the angle of the beam DF at point D, respectively. These boundary conditions solved by the deflection equation of the beam AB (and DF),

$$EI\frac{d^2y}{dx^2} = R_B(\delta_D - y)\sin\phi + R_B x\cos\phi.$$

Therefore,

$$\begin{aligned}\delta_B &= \delta_B(1-\cos k_1 l_1) - \frac{\cot\phi}{k_1}\sin k_1 l_1 + l_1\cot\phi,\\ \delta_D &= \delta_D(1-\cos k_2 l_1) - \frac{\cot\phi}{k_2}\sin k_2 l_1 - l_1\cot\phi,\\ \theta_B &= \delta_B k_1 \sin k_1 l_1 - \cot\phi\cos k_1 l_1 + \cot\phi,\\ \theta_D &= \delta_D k_2 \sin k_2 l_1 + \cot\phi\cos k_2 l_1 - \cot\phi,\\ k_1 &= \sqrt{\frac{W(b-l_1\cos\phi+d)\sin\phi}{2EI}},\\ k_2 &= \sqrt{\frac{W(b-l_1\cos\phi-d)\sin\phi}{2EI}}.\end{aligned}$$

Then, from the equation (6)

$$y_c(0) = \frac{1}{EI}c_2 = -\delta_B\cos(\phi-\theta_B) \qquad (7)$$

From the equations (4)–(7), we determine the c_i (i=1,2). Finally, we obtain the angle θ_c at point C as a function of l_1 and ϕ,

$$\begin{aligned}\theta_c &= f(l_1,\phi)\\ &= \frac{W(b-l_1\cos\phi)(b-l_1\cos\phi+d)}{6EI}\\ &\quad + \frac{1}{2(b-l_1\cos\phi)}\{\delta_B\cos(\phi-\theta_B)+\delta_D\cos(\phi-\theta_D)\}. \qquad (8)\end{aligned}$$

By using equation (8), we can simulate the deformation angle at point C in Fig. 4.

ACKNOWLEDGMENT

We express our sincere thanks to Prof. Masazumi Okajima for his support in this work.

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