System Level Analysis for a Locomotive Inspection Robot with Integrated Microsystems

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ABSTRACT

In this paper, we describe the system level analysis for the inchworm-like locomotion based inspection robot that is integrated with micro components such as a micro pump, micro channels, micro suction system, and linear actuators with micro channel. Using the system level analysis software COVENTOWARE SABER and the system modeling software Matlab, the required specifications of each component were decided and the simplified clamping device was fabricated based on this analysis result. The comparison between the theoretical data and the experimental data shows the validity of this approach method.

Keywords: System level analysis, locomotion, inspection, microsystems, robot.

1 INTRODUCTION

Recently there have been many attempts to develop locomotive micro-robots for various purposes [1,2]. These micro robots, however, have its limitations on the application in the medical area because the organic environment is very slippery and non-uniform. Because the tissue can be deformed greatly, it is not easy to make locomotive devices for this environment. Some bio-oriented previous researches showed that a bio-mimetic approach, inchworm locomotion, could give a solution in the organic environment [3,4]. The locomotive sequence based on the suction clamping and linear actuation showed good locomotive performance. To implement this principle for a small micro robot, it is necessary to integrate small micro components such as micro vacuum sources and linear actuators into the biocompatible robot body. For this purpose, we proposed a micro locomotive robot as shown in Figure 1 that comprises a micro pump for the vacuum generation, a linear actuator made of both polymer elastomer and the shape memory alloy wire, and micro channels for the suction clamping. Because parameters of micro components affect greatly other components' performance, the system level analysis and parameter tuning are essential procedures in designing micro integrated systems like the proposed micro robot.

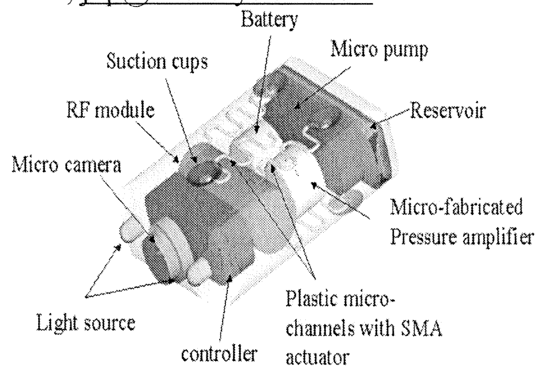

Figure 1: Concept of the proposed micro inspection robot

In this paper, we modeled the proposed micro robot on system level and analyzed the suction clamping performance and important design parameters of each component based on the analysis result. In designing micro integrated system, it is needed to simplify its components as much as possible. In this point of view, we also propose another simplified suction clamping structure using a simple squeezing pump instead of general micro pumps for the pressure source. For this configuration, we also analyze the suction clamping performance based on the system level analysis. In addition, the concept and the fabrication process of a micro linear actuator composed of a SMA meander actuator and a deformable elastic micro channel is introduced. Some test bench results of the suction-clamping device is also described.

2 MODELING AND ANALYSIS

2.1 Analysis for the clamping device

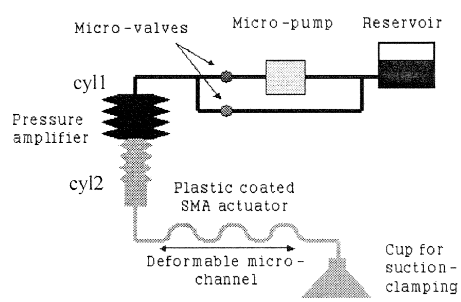

Figure 2: The schematic drawing of the proposed micro locomotive actuators

Figure 2 shows the schematic drawing of the proposed micro locomotive device. This device comprises a micro pump, a reservoir, two micro valves, one micro pressure amplifier, a linear actuator and a suction cup. The micro pump generates required pressure and induces the flow into the pressure amplifier. When the first cylinder (cyl1) increases its volume, the volume of the second cylinder (cyl2) of the pressure amplifier decreases. In this state, the suction cup will be contact with wall or organ wherever the robot wants to attach. After the suction cup is closed with the wall or organ, the pressure in cyl1 is released. Then, the cyl2 tries to increase its volume because of the mechanical stiffness of the bellows. While cyl2 increases its volume, the pressure inside of the cyl2 decreases under the atmosphere pressure and the suction force is generated due to the low pressure. The role of the pressure amplifier is to amplify the effect of pressure drop inside of the cyl2 by using the force equilibrium between the first cylinder and the second cylinder. Using different sectional areas of the first cylinder and second cylinder, the pressure drop is magnified. When the two bellows are connected directly, we can calculate the pressure induced on the second bellow by considering the force equilibrium between the two bellows as equation (1).

$$P_{cyl2} = \frac{A_{cyl1}}{A_{cyl2}} \cdot P_{cyl1} \qquad (1)$$

The pressure loss from the micro pump to the cyl1 through a micro channel can be described as equation (2) by using Hagen-poiseuille equation. The pressure induced at cyl1 of the pressure amplifier can be described as equation (3) with the consideration of the accumulated fluid. The required pressure of the micro pump can be derived as equation (4) by combining equation (2) and equation (3). The pressure that can be generated from the micro pump should be calculated in consideration of its power as equation (5). Using equation (4) and equation (5), the response of the suction clamping system can be estimated with various pump powers and various micro-channels.

$$\Delta P = \frac{128 \cdot \mu \cdot l}{\pi \cdot D^4} Q \qquad (2)$$

$$P_2(t) = \frac{k \cdot \delta x}{A} = \frac{k}{A}\left(\frac{1}{A}\int Q(t)dt\right) = \frac{k}{A^2}\int Q(t)dt \qquad (3)$$

$$P_1(t) = C \cdot Q(t) + P_2(t) = C \cdot Q(t) + \frac{k}{A^2}\int Q(t)dt \qquad (4)$$

Where, $C = \frac{128 \cdot \mu \cdot l}{\pi \cdot D^4}$

$$P_{1\_real}(t) = \min\left(P_1(t), \frac{\mu \cdot P_w}{Q(t)}\right) \qquad (5)$$

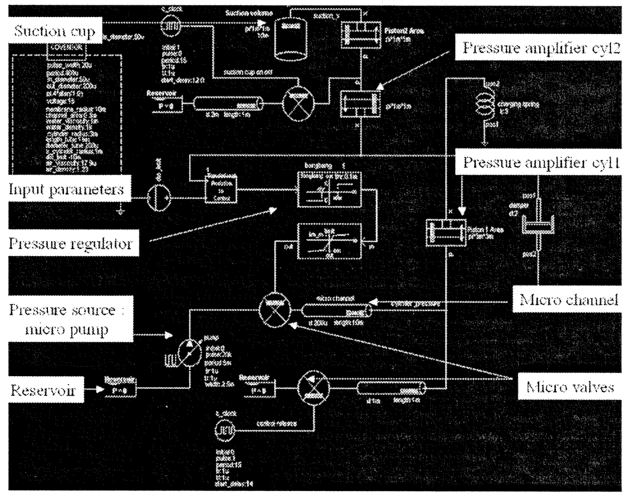

Figure 3: The simplified schematic drawing of the component

The proposed clamping device was analyzed by using the COVENTOWARE, SABER as shown in figure 3. Based on this model, the behavior of the components was evaluated under parameter variations. Figure 4 shows the clamping preparation time, one of the important criteria of the clamping system with micro channels. Figure 5 shows the behavior of the flow inside of the micro channel between the micro pump and cyl1 and it also shows the operational behavior of the micro pump. By using these analyses, the important parameters of the clamping device were selected as shown in table 1.

Table 1. Designed parameter

	Designed value	Amplification effect	Pump Power	Time	ΔP
cyl 1	3 mm	8.42	0.05 μW	85 sec	9kPa
cyl 2	1 mm				
Suction cup	3 mm				
Spring stiffness	3 N/m				

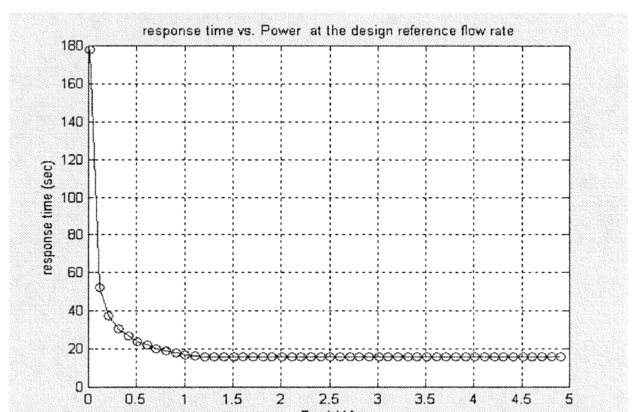

Figure 4: the clamping preparation time with various micro pump powers

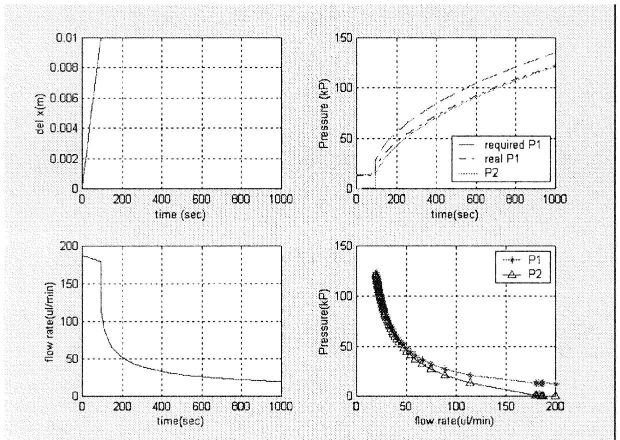

Figure 5: The operational behavior of the micro pump

2.2 Simplified clamping device

To embody the proposed clamping device, we can use a simple pump as the pressure source instead of the general micro pump made of the PZT membrane. We invented a simple squeezing type micro pump composed of a bellow and the SMA coil spring. When the SMA coil spring is activated, the length of the spring decreases and the positive pressure is generated inside of the bellow. Figure 6 shows the schematic drawing of the simplified clamping device. When the SMA actuators are heated, the bellow is squeezed. The pressure generated from the squeezing pump can be calculated as equation (6). After the induced pressure released with the closed suction cup, the negative pressure is generated at the suction cup A_4. So, the clamping force from the negative pressure can be calculated as equation (7).

$$P_2 = \frac{(K_2 + K_3)}{A_2} \cdot \Delta X_2 + P_{atm} \qquad (6)$$

Where,

$$\Delta X_2 = \frac{A_1}{A_2} \cdot \Delta X_0$$

$$\Delta X_0 = \frac{KH_{sma} \cdot \Delta X_{sma} - K_{bellow} \cdot \Delta X_{bellow}}{(K_2 + K_3) \cdot (\frac{A_1}{A_2})^2 + (K_{bellow} + KH_{sma})}$$

$$P_{final} = P_{atm} - (K_2 + K_3) \cdot \Delta X_{x\_final} / A_3 \qquad (7)$$

$$PI = \left(1 - \left|\frac{F_{clamping} - F_{required}}{F_{required}}\right|\right) \cdot W_1 + \left(1 - \left|\frac{\Delta X_2 - \Delta X_{2\_ref}}{\Delta X_{2\_ref}}\right|\right) \cdot W_2 \qquad (8)$$
$$+ \left(1 - \left|\frac{KH_{sma}}{\max(KH_{sma})}\right|\right) \cdot W_3$$

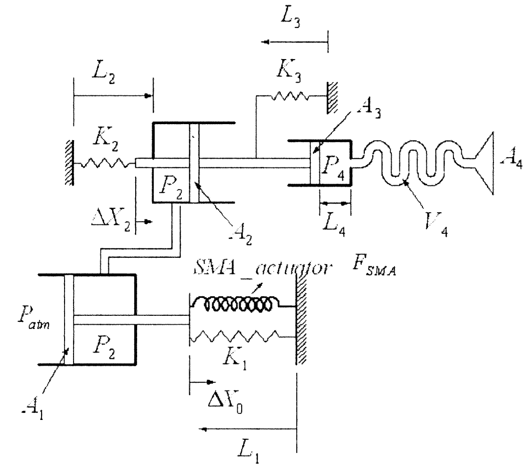

Figure 6: The schematic drawing of the simplified clamping device.

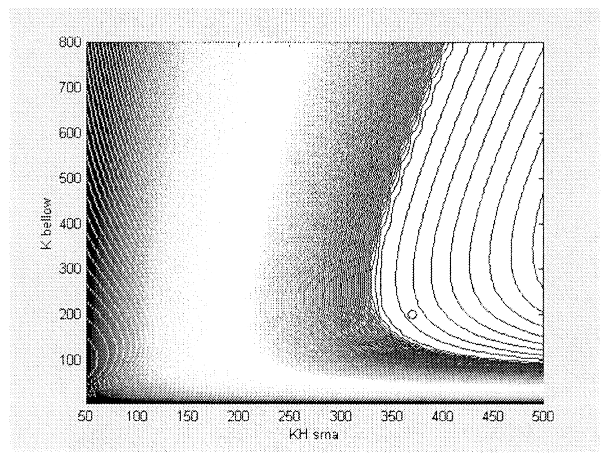

Figure 7: The Performance Index changes with various K_{bellow} and KH_{sma} values

When we define the performance index PI as the sum of the normalized clamping force, ΔX_2 and the stiffness of the SMA, it can be expressed as equation (8) and this is the function of K_{bellow} and KH_{sma}. The performance index varies with the change of inner parameter such as K_{bellow} and KH_{sma} as shown in figure 7. We selected the optimal stiffness values for the SMA spring and the bellow based on system modeling based analysis as 375 N/m and 200 N/m respectively.

2.3 Linear actuator with the SMA spring and deformable micro channel

To move the robot body forward or backward, the clamping device needs to be integrated with linear actuators. Therefore, we propose a new linear actuator composed of deformable polymer micro channel and the SMA spring. When the pre-tensioned SMA spring is assembled with the elastomer, the length of the SMA spring changes according to the temperature. The proposed robot, however, uses the suction clamping devices. So, the linear actuator should have a micro channel inside of it. By making the meander shape SMA spring and deformable meander micro channel, the linear actuator can be assembled. The deformable micro channel can be made of the PDMS (Polydimethylsiloxane) by using micro molding process as proposed in figure 8. Figure 9 shows the combination of the micro channel and the SMA spring.

3 FABRICATION AND EXPERIMENTS

The prototypes of the proposed suction clamping devices are fabricated as shown in figure 10. The mold for the deformable micro channel was fabricated by using mainly Deep RIE. After the micro channel is cast on the mold, it was assembled with the SMA meander spring. We also fabricated the suction cup by using PDMS. The clamping performance using the vacuum pressure was evaluated by using bench test. Figure 11 shows the test result with the suction cup (diameter: 9mm, PDMS). This shows good clamping performance of the suction cup on the tissue. The generated clamping forces on acryl and tissue by using the squeezing pump (figure 10) were 50.1 gf and 17.9 gf respectively.

4 CONCLUSIONS

A locomotive micro inspection robot composed of micro components such as a micro pressure source, a pressure amplifier, a deformable elastic micro channel and a suction cup is proposed. Based on the system level analysis, the fine parameters were tuned in consideration of the layout of the micro robot and the dimensional constraints. A linear actuator for micro robot with deformable micro channel and the SMA actuator is also proposed and fabricated with the micro molding method from the MEMS technology. For the future work, we need to assemble the total system and test at the real environment.

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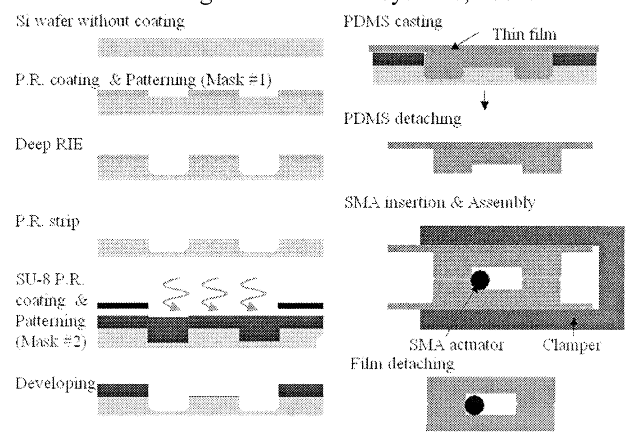

Figure 8: The micro molding process for PDMS elastomer

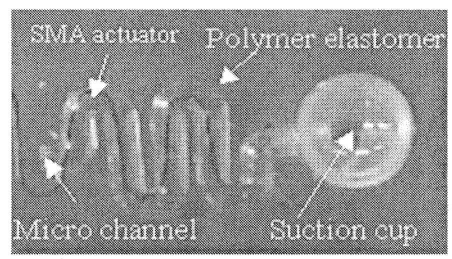

Figure 9 : The linear actuator with the SMA actuator and elastic polymer micro channel.

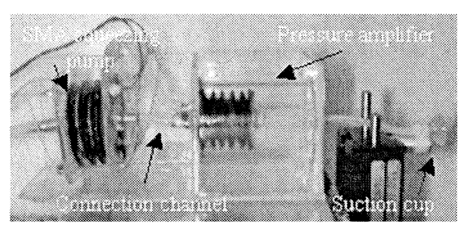

Figure 10 : The prototypes of the clamping device

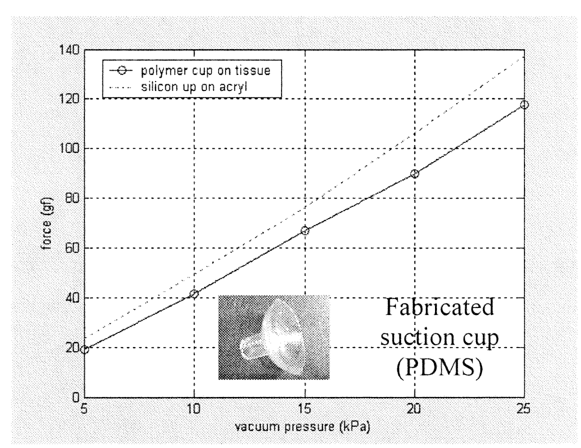

Figure 11 : The clamping force with suction clamping