졸업논문청구논문

SCP로 작동하는 Antagonistic Robot Arm 의 공냉에 의한 지속 가능한 제어

SCP-Powered Antagonistic Robot Arm's Sustainable Control by Forced Air-Cooling

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SCP-Powered Antagonistic Robot Arm's Sustainable Control by Forced Air-Cooling

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A thesis submitted to the Gyeonggi Science Highschool in partial fulfillment of the requirements for the graduation. The study was conducted in accordance with Code of Research Ethics.[1]

2016. X. X

Approved by
Teacher Oh, Jeonghyeon
[Thesis Advisor]

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박 승 원

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Abstract

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초 록

초록(요약문)은 가장 마지막에 작성한다. 연구한 내용, 즉 본론부터 요약한다. 서론 요약은 하지 않는다. 대개 첫 문장은 연구 주제 (+방법을 핵심적으로 나타낼 수 있는 문구: 실험적으로, 이론적으로, 시뮬레이션을 통해)를 쓴다. 다음으로 연구 방법을 요약한다. 선행 연구들과 구별되는 특징을 중심으로 쓴다. 뚜렷한 특징이 없다면 연구방법은 안써도 상관없다. 다음으로 연구 결과를 쓴다. 연구 결과는 추론을 담지 않고, 객관적으로 서술한다. 마지막으로 결론을 쓴다. 이 연구를 통해 주장하고자 하는 바를 간략히 쓴다. 요약문 전체에서 연구 결과와 결론이 차지하는 비율이 절반이 넘도록 한다. 읽는 이가 요약문으로부터 얻으려는 정보는 연구 결과와 결론이기 때문이다. 연구 결과만 레포트하는 논문인 경우, 결론을 쓰지 않는 경우도 있다.

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I. Introduction

Artificial muscles have been largely studied in Robotics for performing human's delicate movement [1]. Recently, super-coiled polymer(SCP) artificial muscle and its striking features were discovered by Haines *et al.* [2] SCP artificial muscle is a new kind of artificial muscle which can be easily fabricated by simply twisting a nylon thread excessively. This artificial muscle contracts when heated and relaxes when cooled.

Since SCP artificial muscle can provide fast [3], nonhysteretic[Citation Needed], strong[Citation Needed], and large stroke[Citation Needed]with low cost [4], it will be an important milestone to modern Robotics. But, appropriate circumstances for SCP artificial muscle must be studied to apply this artificial muscle into robots.

In Haines *et al.*, it presents SCP artificial muscle 's heating method - fabricating SCP artificial muscle with silver coated nylon thread and applying electric current, which provides Joule heat to muscle [2]. This method was checked and applied by Mirvakili *et al.*and Yip *et al.* [3,4] However, methods for cooling SCP artificial muscle have been largely unsuccessful to date. Cooling by water flow was used in Haines *et al.*, but it may cause life shortage of SCP artificial muscle [2], and hard to apply on robots. Also, cooling fan was used in Yip *et al.*, but it didn't get sufficiently fast cooling speed.

In this paper antagonistic robot arm, which actuates by two of the complementarily contracting SCP artificial muscle, was assemblied and its operating system was attached. Also, behavior of SCP artificial muscle and antagonistic robot arm was simply modeled with linear equations and tested experimentally. By quantifying thermal conductivity, possibility of feedback cooling was confirmed. In conclusion, algorithms for sustainable antagonistic position control was designed, performed, and simulated.

II. Preparation of muscle and system

SCP artificial muscle responses as a function of temperature. In order to precisely control the complicated system, electrical microprocessor was used. Therefore, in this section, the method for electrically operating SCP artificial muscle and investigating its characteristic is discussed.

2.1 Fabrication of SCP artificial muscle

The SCP artificial muscle used in this paper was made by twisting silver-painted nylon thread (Conductive Sewing Thread Size 92, Shieldex), which were found to be best in terms of strain and force production [2]. First, as shown as Fig.1a, conductive thread was piled up four times to make its length be 50 cm. Each side of thread was connected to washers. Then, wire was hung(Fig.1b) to one of the washer and motor to the other(Fig.1c). Motor was rotated until thread creates coil [5].(Fig.1d) After making same one again, two coils were overlapped to each other, making stable form.(Fig. 1e,1f) Lastly, by applying electric current, they were treated with heat.[2] By this method, we made a SCP artificial muscle which is 10 cm - 11 cm in length and 2.5 Ω in electric resistance at ambient temperature with no external force.

2.2 Electrical control of SCP artificial muscle

As discussed in previous section, SCP artificial muscle was made with conductive thread in order to electrically control heat speed. Electrical resistance of SCP artificial muscle was $R = 2.5\,\Omega$, so the power P was supplied by applying voltage $V = \sqrt{PR}$. The voltage was controlled by MOSFET and PWM generation of Arduino Uno.

In order to implement faster cooling speed of SCP artificial muscle , compressed air tank and solenoid valve was used. Air tank forces air(temperature : equals to $T_{ambient}$) to flow around SCP

[2] 2.5 A of electric current was applied and stopped when smoke occurred. While repeating heating and cooling about ten times, the length at ambient temperature got longer and reaches constant length.

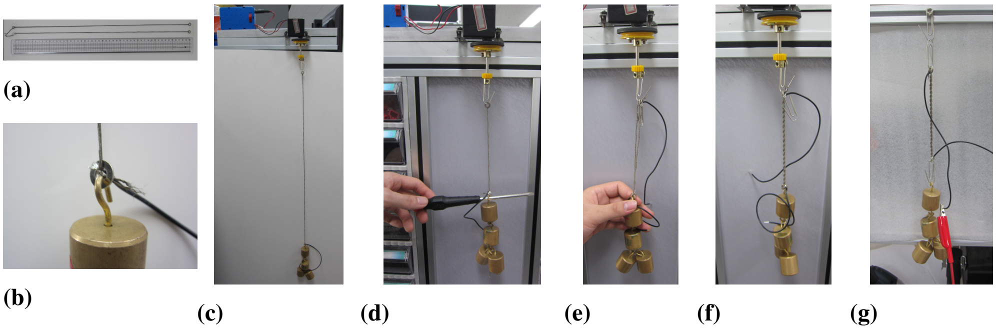


Fig. 1. Process of making SCP artificial muscle with silver-painted nylon thread. (a) 4-ply, 50 cm thread bundle's each side was hung on washers. (b)(c) Up side was hung on motor, and down side was hung on 400 g weight with wire inserted in between washer and thread. (d) In order to twist thread until it creates coil, down side was fixed with a stick. (e) By repeating process (a) - (d), two super coiled polymer was made. Their up side were hung on one clip. Also, their down side were hung on 400 g weight, which is same as (c). (f) By these processes, SCP artificial muscle was made, which has wire on each side. (g) Finally, they were annealed until length at ambient temperature doesn't get longer.

artificial muscle , so we can significantly increase the thermal conductivity λ of muscle. Meanwhile, the amount of air flow can't be analog controlled. Therefore, by stopping and resuming flow of air with an appropriate period and ratio, we can control the thermal conductivity λ of muscle. This will be discussed at section 3.4 on a closer view.

2.3 Physical Measurements of SCP artificial muscle

Physical properties of SCP artificial muscle , such as temperature, length, and tension, was measured with various sensors. [3] SMD type temperature sensor was used to measure the temperature of SCP artificial muscle without effecting the specific heat of SCP artificial muscle .

Also, slide potentiometer was used to measure the linear displacement of SCP artificial muscle . But, since it had significant amount of friction, it was only used for experiments about SCP artificial muscle 's characteristics. On the other hand, rotary sensor, which had low frictional torque, was used to make an antagonistic robot arm .

To measure the tension of SCP artificial muscle , load cell and amplifier was used. Load cell played a role of connecting SCP artificial muscle and skeleton of antagonistic robot arm .

[3]For detail information of following sensors, see Table A-1.

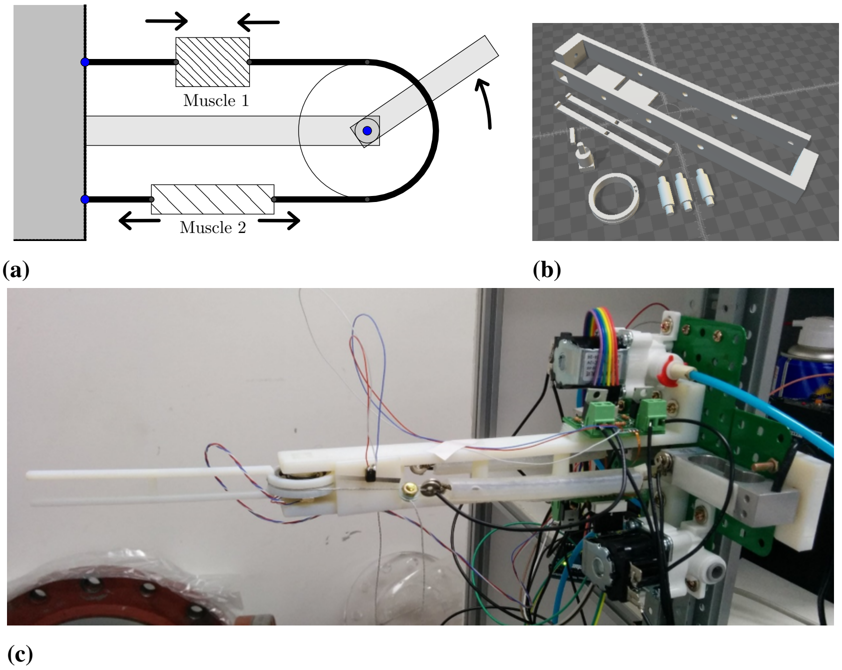


Fig. 2. (a) By contracting two SCP artificial muscles complementarily, we can get same effect of cooling one muscle by heating another. (b) The skeleton of antagonistic robot arm was designed with software(3D Builder, Microsoft) and 3d-printed. (c) An overall image of antagonistic robot arm .

2.4 An Antagonistic Robot Arm

SCP artificial muscle can be easily heated by applying electric current. However, cooling demands more sophisticated procedure. Also, muscles can only produce strong force while contracting. This means that SCP artificial muscle can't be directly applied to robots which have to produce force on various position. Therefore, we designed an antagonistic robot arm, so that the system is energy-optimal for various tasks [6].

III. Experiments

In order to plan a strategy for controlling the tension and length of SCP artificial muscles, its character must be modeled with mathematical equations. In this section, behavior of SCP artificial muscle was modeled with linear equations and verified by three kinds of experiments. Therefore, equation of antagonistic robot arm was obtained.

3.1 Modeling of Antagonistic Robot Arm

SCP artificial muscle can be expressed as an combination of mechanical model and thermal constant. The correlation between muscle's displacement x, temperature T, elastic constant k, damping constant b, thermal constant c and tension F is shown in (1) [4].

$$F = k(x - x_0) + b\dot{x} + c(T - T_0) \tag{1}$$

Also, by considering Newton's cooling law, the correlation between specific heat C_{th} and thermal conductivity λ can be expressed as (2) [4].

$$C_{th}\frac{dT(t)}{dt} = P(t) - \lambda(T(t) - T_{ambient}) \tag{2}$$

Since antagonistic robot arm is sum of two SCP artificial muscle , the displacement of two SCP artificial muscle is complementarily(Fig.3b). If one of the muscle's displacement is expressed as Δx, another is $-\Delta x$. Therefore, torque τ of arm can be expressed as (3). Also, by considering $\Delta x = r\theta$ and $\tau = J\ddot{\theta}$, arm's equation of motion is (4), where r, θ and J is radius of arm, rotational displacement, and moment of inertia, respectively.

$$\tau = [-k\Delta x - b\dot{\Delta x} + c(T_1 - T_0) - (k\Delta x + b\dot{\Delta x} + c(T_2 - T_0))]r \tag{3}$$

$$J\ddot{\theta} + 2br^2\dot{\theta} + 2kr^2\theta = cr(T_1 - T_2) \tag{4}$$

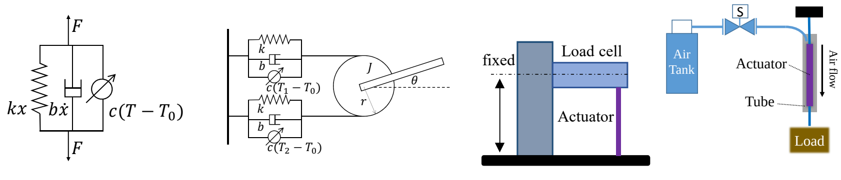
3.2 Aims and Experiment Apparatuses

In order to verify and measure constants of model discussed in section 3.1, two kinds of experiments were carried out - static, and dynamic experiment. The aims of the experiments are shown below.

1. As shown in equation (1), to check that muscle's tension changes in respect to length linearly, and to observe a bit of hysteresis caused by $\dot{x}$.
2. To check that muscle's tension changes in respect to temperature linearly.
3. As shown in equation (2), to check that temperature of muscle changes exponentially and converges to T_{steady} when constant power is supplied.
4. To confirm that $T_{steady} - T_{ambient}$ is proportional to supplied power and get its factor.
5. To quantify thermal conductivity of muscle when it is cooled with air flow.

In order to achieve first and second aim in section 3.2, we conducted 'static experiment' by using following apparatus : An E-shaped holder that holds each side of SCP artificial muscle to maintain constant length which can be customized. (Fig.3c) Additionally, load cell, temperature sensor, and slide potentiometer was used to measure tension, temperature, and length of SCP artificial muscle, respectively. Also, voltage between muscle was measured to calculate applied power of muscle. These sensors are all connected to NI cRIO-9024 for synchronized real-time data acquisition.

In order to achieve third, fourth, and fifth aim in section 3.2, we conducted 'dynamic experiment' by using following apparatus : As shown in Fig.3d, air can, solenoid valve, and tube which surrounds actuator is connected in sequence. Load was hung on the end in order to prevent muscle becoming loose. Also, temperature sensor was tightly attached to muscle, and connected to Arduino Uno for synchronized real-time data acquisition.



(a) **(b)** **(c)** **(d)**

Fig. 3. (a) SCP artificial muscle can be expressed as an combination of a spring, damper, and temperature-dependent system. (b) Antagonistic robot arm can be expressed with two complimentary muscles, which change the angular position. (c) Scheme of static experiment. (d) Scheme of dynamic experiment.

3.3 Static experiment

The aim of static experiment was to verify equation (1) and achieve first and second aim in section 3.2. In other words, correlation of SCP artificial muscle's length and tension was investigated at various temperature.

We can say that muscle have a length l_0 at ambient temperature with 0 N tension. Taking l_0 as standard, we conducted experiments by changing length 15 mm gradually. Also, we used five kinds of voltage - 0 V, 1.0 V, 1.8 V, 2.2 V, 2.6 V.

1. Initial length of SCP artificial muscle was adjusted to l_0.
2. We started to apply constant voltage to muscle and waited until muscle's length and temperature becomes steady.
3. When muscle becomes steady, we started recording its physical properties, such as length, tension, temperature, and time.
4. We gradually increased the length of muscle to $l_0 + d$.
5. We gradually decreased the length of muscle to l_0.
6. End of recording. After cooling to ambient temperature, we repeated 1-5 with other voltage.

Results of static experiment is shown in Fig.4. Each of the temperature indicated in legend corresponds to T_{steady}. In Fig.4a, we can observe slight hysteresis. This characteristic graph can be linearly regressed as Fig.4b. Also, by obtaining force at 10% strain for each temperature,

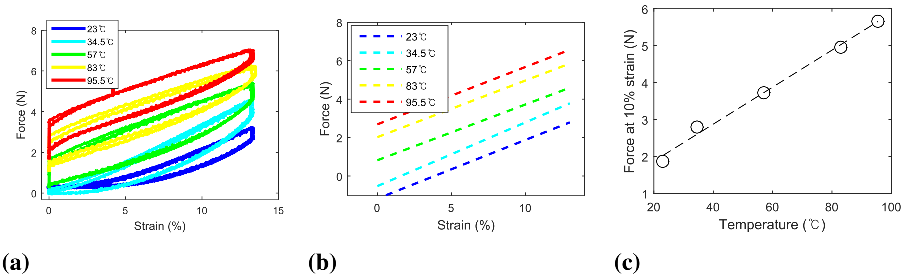


Fig. 4. Result of Static experiment. (a) Characteristic curves of SCP artificial muscle for various T_{steady}. (b) Linear graph of correlation between tension(force) and strain. (c) Tension is linearly proportional to T_{steady}.

we can check that force is linearly proportional to T_{steady}. By analyzing graph in Fig.4a, we got values of k, c in (1).

$$k = 304\,\mathrm{N/m}, c = 0.0501\,\mathrm{N/^{\circ}C}$$

3.4 Dynamic experiment

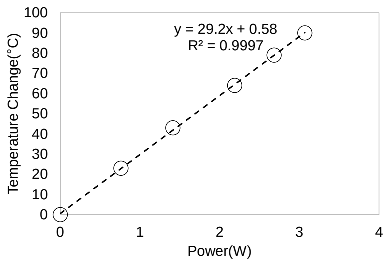
The aim of dynamic experiment was to achieve third to fifth aims in section 3.2.

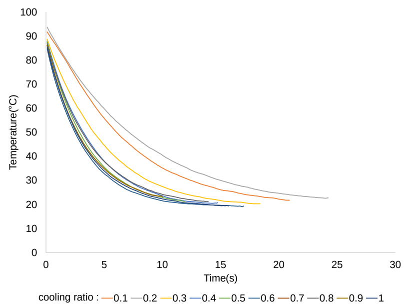
As introduced in section 2.2, forced air flow was periodically stopped and resumed to control thermal conductivity of SCP artificial muscle. This was done by opening the solenoid valve for constant ratio at each period. For example, if we make valve to be opened for 70 ms and closed for 30 ms, the ratio will be 70%. From now on, we will call this as 'cooling ratio' and use variable name r.

The period of opening and closing was 100 ms, which was carefully chosen to get best performance. If the period is too long, thermal conductivity of SCP artificial muscle will periodically change. On the other hand, if the period is too short, the solenoid valve won't perform well because it will take minimal time to close the valve.

We followed a following process to do dynamic experiment. An Arduino code for dynamic experiment is shown in section 1. We used constant voltage - 2.59 V. Cooling ratio was variously changed, including 0(Natural cooling, λ_N), and 1(Complete forced cooling, λ_F).

1. When muscle is begin $T = T_{ambient}$, we started recording time and temperature.





(a) **(b)**

Fig. 5. (a) Temperature changes proportionally to power. (b) After power was shut down and forced cooling had began, temperature decreased exponentially.

2. Constant power was applied until it reaches steady state.
3. After reaching $T = T_{steady}$, power was disconnected and cooling was started.
4. When muscle's temperature reaches $T = T_{ambient}$ again, we stopped recording. We repeated process 1-3 with other voltage and cooling ratio.

First, by graphing the relation between power P and temperature shift $\Delta T = T_{steady} - T_{ambient}$, we could check that they are linearly proportional, as shown in (5). The thermal conductivity of SCP artificial musclewas calculated from slope of $\Delta T - P$ graph in Fig.5a.

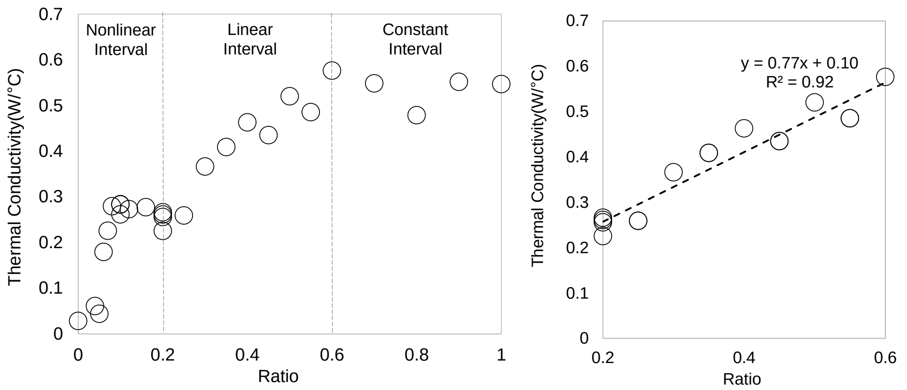
Also, we could check that temperature of SCP artificial muscle changes exponentially as shown in Fig. 5b. This was in line with (2).

$$P = \lambda \Delta T \tag{5}$$

Next, by applying (5) into heating graph, we could get λ_N according to Fig.5a. Then, by calculating time constant of heating graph, we could calculate SCP artificial muscle system's specific heat C_{th} with (6).[4]

$$\lambda_N = 3.42 \times 10^{-2}\,\mathrm{W/^\circ C}, C_{th} = 1.81\,\mathrm{J/^\circ C}$$

[4]This was measured three times, resulting 51.3 s, 54.1 s, 53.0 s. Average was 52.8 s.



(a) **(b)**

Fig. 6. (a) λ was linearly proportional to cooling ratio r when $0.2 < r < 0.6$. (b) λ can be calculated with equation (7).

Now, we have value of C_{th}, so thermal conductivity can be obtained by using (6). Analysis for each cooling graphs is shown in Fig.6.

$$\lambda = \frac{C_{th}}{\tau} \tag{6}$$

In Fig.6a, we could observe that thermal conductivity in function of r can be divided into three parts - nonlinear, linear, and constant interval. If $r < 0.2$, λ rapidly increased near $r = 0.1$. Also, λ doesn't increased anymore if $r > 0.6$, *i.e.* $\lambda = \lambda_F$. Therefore, the linear interval was chosen for Antagonistic position control.

$$\lambda = 0.77 \cdot r + 0.10(\mathrm{W/°C}), 0.2 \leq r \leq 0.6 \tag{7}$$

Meanwhile, we have to check that the load used in dynamic experiment doesn't effected muscle's thermal power. Total electrical power of muscle is about $(1.0\,\mathrm{V})^2/(2.5\,\Omega) = 0.4\,\mathrm{W}$, cooling speed is about $1.39\,\mathrm{J/°C} \cdot 1\,\mathrm{°C/s} = 1.39\,\mathrm{W}$ while gravitational power is about $0.4\,\mathrm{kg} \cdot 9.8\,\mathrm{m/s} \cdot 0.001\,\mathrm{m/s} = 0.004\,\mathrm{W}$. So we can conclude that load didn't affected on measurement of muscle's thermal properties.

IV. Control

In the previous section, mathematical modeling of SCP artificial muscle was discussed. In this section, control strategies and their results are shown. Based on models in section 3, antagonistic robot arm was controlled to follow desired position, which is a function of time. We will now call this as Antagonistic position control.

4.1 Basic Strategy of Antagonistic Position Control

By assuming that $\ddot{\theta}$ and $\dot{\theta}$ is small enough, we can get correlation between θ and T_1, T_2 as (8).

$$\theta = \frac{c}{2kr}(T_1 - T_2) \tag{8}$$

By multiplying Laplace transformation of (2) and (8), we can get transfer function of P and θ as (9).

$$\frac{\theta(s)}{P(s)} = \frac{c/2kr}{C_{th}s + \lambda} \tag{9}$$

Therefore, process of controlling θ into θ_{ref} by applying constant power can be shown as block diagram in Fig.7b.

In this situation, $K_{\theta,P}$ is constant. By applying constant power to only one of the muscle, θ at steady state was measured. Linear fitting of Fig.7a gives us following constant.

$$K_{\theta,P} = 0.185\,\mathrm{W}/^{\circ}$$

For fast and precise control, lead compensator was added and feedback, feedforward was applied, as can be seen in Fig.7c, 7d.

4.2 Antagonistic Position Control Strategy for Making Sin Wave Motion

In this section, we aim to make a simple sin wave motion of antagonistic robot arm like (11). By doing this, we could check the possibility of antagonistic position control for any complicated motion. Basically, according to the equation (8), we can increase θ by heating muscle 1 and decrease θ by heating muscle 2. By assuming that $\ddot{\theta}$ and $\dot{\theta}$ is small enough, (4) can be approximated into (10).

$$\theta = \frac{c}{2kr}(T_1 - T_2) \tag{10}$$

Therefore, we used a strategy shown in Table.1

$$\theta_{ref}(t) = (9^\circ)\sin(2\pi 0.025t) \tag{11}$$

Table 1. Basic strategy of antagonistic position control for making sin wave motion.

Time(s)	0-10	10-20	20-30	30-40
Muscle 1	Heat	Keep	Keep	Heat
Muscle 2	Keep	Heat	Heat	Keep
θ	increase	decrease	decrease	increase

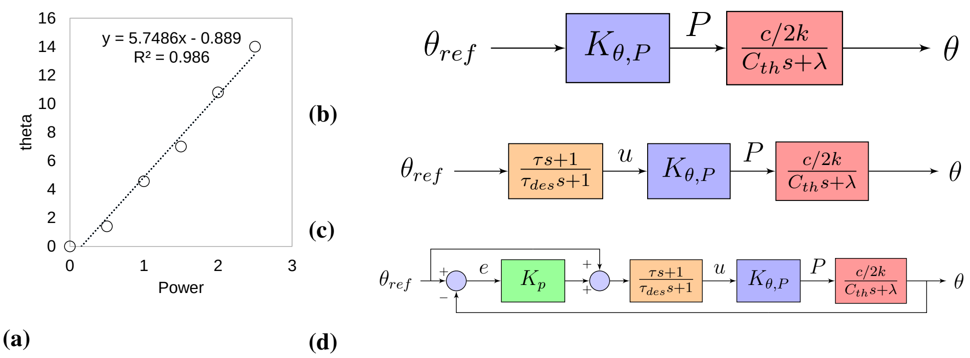
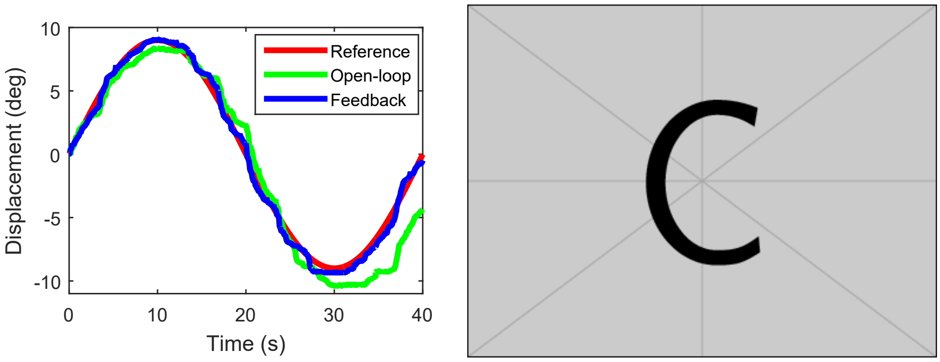


Fig. 7. Block diagrams for antagonistic position control .(a) There's a linear relationship between applied power and θ at steady state. (b) Process of obtaining desired angle with constant power (c) Process of antagonistic position control including lead compensator (d) Process of antagonistic position control including feedback and feedforward



(a) **(b)**

Fig. 8. Antagonistic Position Control by only heating. (a) Measured arm's angular position in function of time. Feedback control had smaller error than open-loop control. (b) Used power of each SCP artificial muscles(Open loop)

Since the Laplace transformation of (11) is too complicated, we used an approximation shown in (12) by dividing (11) into 12 steps. In this case, demanded power can be calculated as (13). ($n = 12$) [5]

$$\theta_{ref}(t) = \sum_{i=0}^{n-1} (\theta_{ref,i+1} - \theta_{ref,i}) U(t - i\Delta T) \tag{12}$$

$$P(t) = \theta_{ref} K_{\theta,P} (1 + (\frac{\theta_{ref} - \theta_{ref,pre}}{\theta_{ref}})(\frac{\tau}{\tau_{des}} - 1) e^{-\frac{t}{\tau_{des}}}) \tag{13}$$

[5] In equation (13), $\theta_{ref,pre}$ is value of θ_{ref} in previous step. Also, t is elapsed time after starting new step.

4.3 Sustainable Antagonistic Position Control Strategy with cooling method

In previous section, the method for making sin wave motion was discussed. But since the temperature of muscle in initial state and final state is significantly different, it won't be sustainable because the temperature will keep going up. Therefore, we need to make the temperature of initial state and final state to be same. This can be done by cooling the muscle during last 1/4 period of sin wave, as shown in table 2.

4.3.1 Demonstration

First, we demonstrated open-loop control of cooling speed. Two-period sin wave control was done, and cooling was done in during t =40 s - 50 s[6]. In order to cool as much as possible, muscle 2 was cooled for all time, and muscle 1 was 'weakly' cooled by repeatedly opening and closing the solenoid valve. As a result, we got an rms error 26.6% for open-loop control, and 6.7% for closed-loop control.(Fig.9)

4.3.2 Simulation

Integrating (6) and (7), we can get (14).

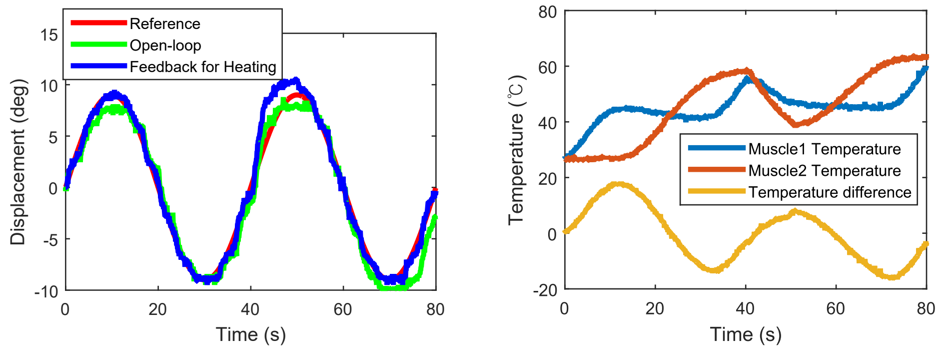
$$\begin{aligned}\tau &= \frac{C_{th}}{\lambda} \\ &= \frac{1.81}{0.77 \cdot r + 0.10}\end{aligned} \tag{14}$$

Also, time derivative of (8) and (11), we can get (15) where t is time elapsed since $t = 30\,\mathrm{s}$.

[6]This slightly differs from table 2.

Table 2. Sustainable Antagonistic position control strategy by using cooling

Time(s)	0	0-10	10-20	20-30	30-40	40
Muscle 1	T_0	Heat	Keep	Keep	Weakly Cool	T_0
Muscle 2	T_0	Keep	Heat	Heat	Strongly Cool	T_0
θ	$0°$	increase	decrease	decrease	increase	$0°$



(a) **(b)**

Fig. 9. Sustainable open-loop antagonistic position control demonstration. (a) Arm's angle in function of time. (b) Temperature of two muscles in function of time. We checked that sustainable antagonistic position control is possible by cooling for some time.

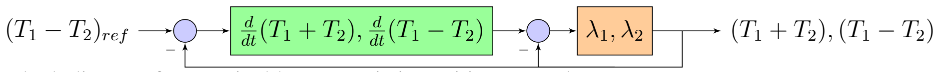


Fig. 10. Block diagram for sustainable antagonistic position control.

$$
\begin{aligned}
\frac{d\theta}{dt} &= \frac{c}{2kr} \cdot \frac{d}{dt}(T_1 - T_2) \\
&= 9^\circ (2\pi \cdot 0.025) \sin 2\pi \cdot 0.025t
\end{aligned}
\tag{15}
$$

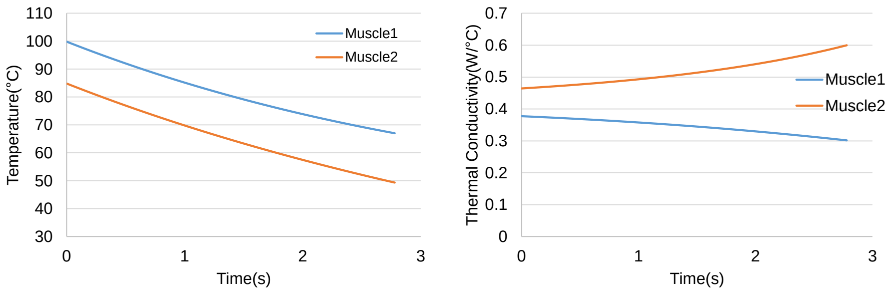
What we have to do is decreasing $(T_1 + T_2)/2$, so we will use following equation with carefully chosen constant $\alpha = 0.23$.

$$
\frac{d}{dt}(T_1 + T_2) = -\alpha(T_1 + T_2 - 2T_{ambient})
$$

Therefore, by using (2) for each muscles, we can calculate needed λ_1, λ_2. The block diagram which represents feedback control of thermal conductivities is shown in Fig.10.

To make sustainable antagonistic position control possible, λ must be between 0.25 W/°C and 0.60 W/°C for all time. Therefore, possibility of this control strategy was verified by thermal simulation.

The limit of thermal conductivity is $0.25 < \lambda < 0.6$, according to (7). In time interval 30 s - 40 s, λ_1 have to decrease and λ_2 have to increase. Therefore, we need to make λ_1 and λ_2 to reach its limit as late as possible. This is determined by constant α. In Fig.9b, we could observe that two of the muscles' average temperature has increased approximately 30 °C. This means that we



(a) **(b)**

Fig. 11. (a) Temperature of two muscles in function of time after $t = 30\,\mathrm{s}$. (b) Thermal conductivity of two muscles in function of time.

have to cool down the average temperature at least 30 °C.

Simulation was carefully done by applying (2) and (4), using the constants we got in section 3. The differential equation was numerically solved with 4th Runge-Kutta method.

Through some times of simulations, we had concluded that $\alpha = 0.23$ is the best. The result of simulation with this value is shown in Fig.11. In Fig.11a, we can observe that average temperature of two muscles had decreased over 30 °C, before reaching limit thermal conductivity as shown in Fig.11b. Therefore, we can conclude that feedback cooling control is possible.

V. Conclusion

Various investigation for method of SCP artificial muscle 's efficient control had been done by prior works [2–4]. However, these studies hadn't established efficient method for cooling SCP artificial muscle . In this study, we tested the performance of cooling method with compressed air can.

We found that thermal conductivity of SCP artificial muscle can be controlled by repeating opening and closing solenoid valve with constant period and variable ratio.

A. List of used materials

Table A-1. List of used materials

항목	품명	제조사	비고
전도성 나일론 실	Conductive Sewing Thread	Shieldex	Size 92
압축공기 캔	Dr.99	BEX Intercorportation	불연성
솔레노이드 밸브	HSV-FF	StormTec	고압용, DC 12V
온도 센서	TC1047AVNB	Microchip	$-40\,°C$-$125\,°C$
Rotary sensor	SV01A103 AEA01B00	Murata	마찰토크 2 mN·m
Slide potentiometer	PTA2043	Bourns	최대 변위 20 mm
Load cell	CB1A	Dacell	CAPA : 3 kgf
신호 증폭기	DN-AM100	Dacell	증폭 100 - 1500배
Arduino Uno	Arduino Uno	arduino.cc	Certified
MOSFET	IRFZ44N	International Rectifier	
PCB	PCB	Devicemart	custom service
볼베어링	깊은홈 볼베어링 6000	KBC	외경 26 mm, 내경 10 mm
데이터 수집 시스템	NI cRIO-9024	National Instruments	Maximum voltage : 10 V

B. Arduino codes

Due to long length, only code for dynamic experiment in section 3.4 is shown. Other codes for antagonistic position control and simulation in section 4.3 is accessible in GitHub. [7]

B.1. Code for dynamic experiment

```
// Measuring Thermal conductivity of air flow induced by Compressed air tank and Arduino-controlled Single Solenoid Valve
// In this experiment, supplied power on muscle is constant
#include "math.h"
const int solvPin1 = 3;
const int tempPin1 = A1;
const int muscPin1 = 11;
const double pi = 3.1416;
int tRead1;
```

[7] URL : https://github.com/seungwonpark/thesis_arduino

```
bool start = false;
int starttime;
unsigned long time;
double t1(){return 125.0*tRead1/256.0-50.0;} // in degrees Celsius

const double r1 = 2.5; // resistance of actuator : 2.5 ohm
const double V1 = 5.00; // Voltage of Power Supply : CONSTANT!!
void musc1(double power){analogWrite(muscPin1, (int)(256*power*r1/V1/V1));}
double ratio = 0;// Time ratio(0 - 1) of SV open : input from serial
double interval = 100.0; // According to experiments, near 50ms is the shortest response time.

void setup() {
Serial.begin(9600);
pinMode(solvPin1,OUTPUT);
pinMode(muscPin1,OUTPUT);
}

void loop() {
int serial_input;
if(Serial.available()){
serial_input = Serial.read(); // By typing 0 - 9 + "Enter", start SV
serial_input -= 48; // '0' - '9' and ':'(colon) : 48 - 57 and 58
ratio = serial_input * 0.1;
start = true;
starttime = millis();
}
if(start == true){
time = millis() - starttime;
tRead1 = analogRead(tempPin1);
dataPrint();
musc1(0.5);
SVsignal();
}
}

void dataPrint(){

Serial.print(time);
Serial.print(" ");
Serial.print(t1());
Serial.print(" ");
Serial.println(" ");
}
void SVsignal(){
digitalWrite(solvPin1, HIGH); // SV doesn't have to be analog controlled
delay(interval*ratio);
digitalWrite(solvPin1, LOW);
delay(interval*(1-ratio));
}
```

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감사의 글

먼저, 2015년 한 해동안 저희의 연구 방향을 제시해 주시고 지도하여 주신 성균관대학교 문형필 교수님께 감사드립니다. 또한, 조교님의 연구만 해도 바쁜 실정인데 저희의 연구에 관심을 가져 주시고 많은 도움을 주신 Luong Anh Tuan 씨에게 감사드립니다. 또한, Luong Anh Tuan 씨 외에도 저희의 연구에 관심을 가져 주시고 조언을 아끼지 않으신 성균관대학교 차세대로봇 액추에이터/센서 연구센터 연구원 분들께 감사드립니다.

저희의 심화 R&E를 교내에서 지도해 주셨으며 교수님을 소개해 주시고, SRC 500호와 같이 교내에 R&E를 진행할 고정적인 장소를 마련해 주셨으며 야간에도 연구 및 안전 지도를 해 주시고, 휴먼테크 논문대회 때 도움을 주셨으며, 졸업논문 지도교사까지도 맡아 주신 오정현 선생님께 너무나도 감사드립니다.

마지막으로, 먼저 저에게 심화 R&E를 같이 하자고 제안해 주고, 2년간 심화 R&E와 졸업 논문을 쓰는 과정에서 동료로써 많은 도움을 준 김형주 학생에게 감사합니다. 형주 덕분에 2년간 정말 많은 것을 배울 수 있었던 것 같습니다. '친구를 잘 두어야 한다'라는 말은 이럴 때 쓰라고 있는 말인 것 같습니다.

연 구 활 동

- 2015 한국영재학회 추계학술대회 영재학교 R&E 및 과학영재교육원 산출물 발표 참가

  - 제목 : SCP Artificial Muscle로 작동하는 Antagonistic Robot Arm의 Feedback 제어
- 2015학년도 제5회 과학영재학교 우수 R&E 공동발표회 참가, KAIST 총장상 수상

  - 제목 : SCP Artificial Muscle로 작동하는 Antagonistic Robot Arm의 Feedback 제어
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  - 제목 : SCP Artificial Muscle로 작동하는 Antagonistic Robot Arm의 Feedback 제어
- 2015학년도 경기과학고등학교 연구대상 수상

  - 제목 : SCP Artificial Muscle로 작동하는 Antagonistic Robot Arm의 Feedback 제어
- 제 62회 경기도과학전람회 참가 예정