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Application of Chemical Reaction Based Pneumatic Power Generator to Robot Finger

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Abstract— **In this paper, a pneumatic power generator based on the chemical reaction is newly proposed by using a small piston pump for the injection of the fuel. Based on the understanding of chemical reaction property, the piston pump is designed by crank-slider mechanism. The piston pump allows compact size and light weight of the entire power generation system compared to the conventional approaches using blow-down tank. In order to verify the effectiveness of the proposed power generation system, we theoretically and experimentally analyze the performance of the system. In addition, we realize the power generator and applies it to an under-actuated robot finger for the feasibility test.**

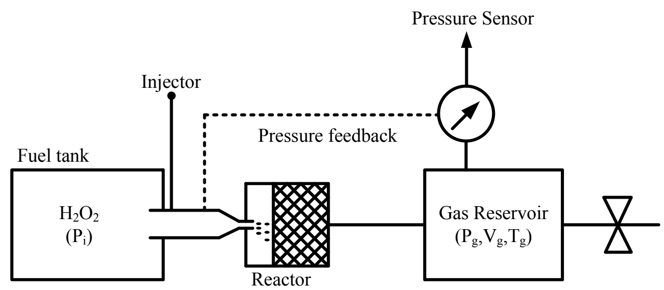

Fig. 1. The schematic of the pneumatic power generator

I. INTRODUCTION

With the development of the technology, the demands for the next generation robots such as humanoid [1], wearable robot [2], and prosthesis [3] have been raising to assist human beings and realize more convenient life. Nevertheless of great efforts of many robotic research groups, their performances still remain in the laboratory level and not satisfactory. Among various problems on control, sensors, and actuators, actuators dominantly influence the performances of the robotic systems. Currently, many of the robotic systems are equipped with geared motors, hydraulic actuator, or pneumatic actuators, but these actuators lead to bulky size and heavy weight of the systems due to the extra devices such as gear box or compressors. For example, motor torques can be enhanced by reduction gears, but it results in the increase of the actuator's weight and the mechanical energy loss [4]. Furthermore, the allowed operating time of the robotic systems actuated by the motors highly depends on the capacity of the battery, which have low energy density. As a result, the robotic systems would be only available in the limited areas such as indoor environments connected to the power line unless the issue on the power source for the robots is solved [5]. In order to overcome the limitation on the conventional actuators, a novel actuator & power system with high power-to-mass ratio and high energy density is essentially required [6]. For these reasons, several researches on the actuator & power system have been recently introduced and developed in [7]∼ [13]. The hybrid hydraulic-electric power unit(HEPU) was developed to generate both hydraulic power for pneumatic actuators and electrical power for controller, sensor and other electrical circuit [7]. HEPU supplies a sufficient amount of power for exoskeleton robot(i.e. BLEEX) [8], but it results in the harmful exhaust constituents such as NO_x and CO_x and high noise levels of 87dB. On the other hand, for eco-friendly approach, the liquid-propellant-powered actuator has been suggested in [9], [10]. High pressure gas was created from the chemical reaction of the liquid hydrogen peroxide(H_2O_2) and stored inside the gas tank. Through the solenoid valve, the gas was supplied for the actuation of the pneumatic system. It was shown that this kind of power systems possess 12.6 times higher actuation potential compared to the battery/motor system. In order to enhance the energetic characteristics of the system, [10] proposed a proportional-injector valve directly supplying pneumatic power to the actuator without storing pressurized gas inside reservoir. In [11], H_2O_2 was used for the chemical fuel of the on-board pressure generation in soft mobile robot. However, since the system uses both oxygen gas and water vapor for the actuation of the pneumatic system, potential corrosion leads to reduced lifetime of the commercial pneumatic components. Besides of using H_2O_2 as a fuel, other chemical fuels were tried for the energy source of the robot system. Deflagration of the sodium azide was used to power the pneumatic actuator [12]. Phase transition of the carbon dioxide at the triple point was also utilized for the fuel of the portable pneumatic power source [13]. But still there remains lots of performance restrictions to be solved.

Designing a small-size and light-weight actuator & power system is still an unsolved problem for the robotic systems, especially in small size robots like prosthetic hand. In our research group, researches on development of light prosthetic hand with high output torque have been proceeding for several years [14]∼ [19], but it is hard to achieve both high performance and light weight of the robot hand. As a result, we realized the importance of the small, light actuator, and

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power system. Motivated by this design challenge, therefore, in this paper, a novel pneumatic power generator using hydrogen peroxide is newly proposed for small size portable robots. A meso-scale injection mechanism of the power system allows to remove the bulky size of blow down tank and remarkably reduces the size and weight of the overall system. For the feasibility test, we design a small size under-actuated robot finger, and it is combined to the pneumatic power generator. Finally, the effectiveness of the proposed pneumatic power system is verified through the experiments.

This paper is organized as follows. In Section II, a concept of the proposed pneumatic power system is introduced. Section III is devoted to the design of the robot finger and presents the experiments with the developed system. Finally, the conclusion follows in Section IV.

II. PNEUMATIC POWER GENERATOR BASED ON CHEMICAL REACTION

A. Description of the system

A schematic of the proposed pneumatic power generator is shown in Fig. 1. The pneumatic power generator consists of four components; a fuel tank, an injector, a reactor, and a gas reservoir. Liquid H_2O_2 solution is stored in a fuel tank. H_2O_2 is injected into the reactor filled with the manganese dioxide (MnO_2) catalyst via the injector driven by a motor. By the catalyst in the reactor, H_2O_2 decomposes into oxygen gas and water vapor. The generated gases are stored at the gas reservoir to produce high pressure pneumatic power. To prevent the corrosion of the pneumatic system and maintain the lifetime of the actuator as long as possible, the water vapor is filtered out from the proposed pneumatic power generator and the only oxygen gas is supplied to the pneumatic system.

B. H_2O_2 Decomposition characteristics

In this paper, H_2O_2 of 70% concentration is fueled to the pneumatic power generator. 70% concentration H_2O_2 has high energy density of 2MJ/kg, which is about 10 times higher than the battery [9]. As described in Eq. (1), the exothermic decomposition process of the H_2O_2 produces the heat energy from the chemical energy stored in H_2O_2 [20]. By heating the generated oxygen and water vapor, the pneumatic power of the system increases.

$$H_2O_2 \rightarrow H_2O + \frac{1}{2}O_2, \quad \Delta H = -98.05kJ/mol \tag{1}$$

Though the energy density of the H_2O_2 is higher than that of the lithium-ion battery, it is low compared to other chemical sources such as gasoline. However, the internal combustion engine is not suitable for the robot systems such as prosthetic hand or exoskeleton because the combustion process is very noisy and even noxious gases such as NO_x and CO_x are emitted during combustion. Unlike gasoline, catalytic decomposition of the hydrogen peroxide is quite silent. In addition, the decomposition of the H_2O_2 generates only oxygen and water vapor, which are harmless to the environment.

For the design of the pneumatic power generator fueled by H_2O_2, the fuel injection rate should be determined to

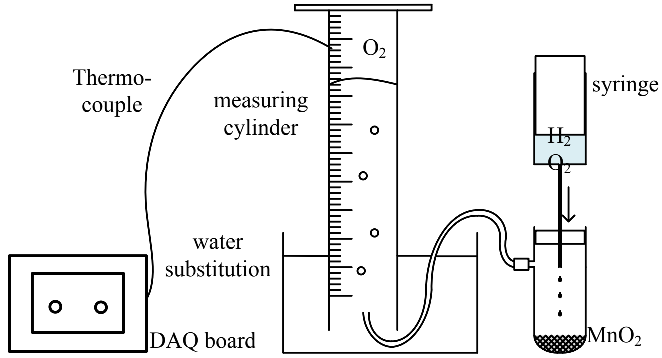

Fig. 2. The open-system experiment setup

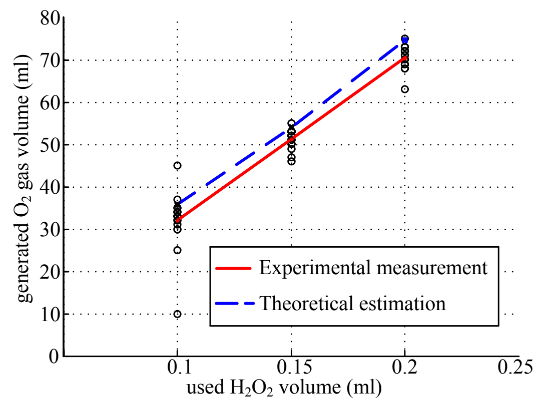

Fig. 3. The decomposition property of H_2O_2

supplement the consumed pneumatic power. Assuming all H_2O_2 is decomposed into water and oxygen, the volume of the generated oxygen gas(y) becomes the function of the temperature(T) and volume of the reacted 70% H_2O_2 solution(x), as shown in Eq. (2). A coefficient, 1.13, is invariable constant obtained by substituting molecular weight, density and other chemical properties of H_2O_2, H_2O and O_2 to Eq. (1).

$$y[ml] = 1.13Tx[ml] \tag{2}$$

Theoretically, during the decomposition of the H_2O_2, the temperature increases more than 600K for adiabatic process. However, by the inevitable heat losses through the reactor wall, the actual temperature of the generated gas is always lower than 600 K. Therefore, we performed the open system experiment to figure out an amount of oxygen gas volume generated for the unit volume of the H_2O_2. As in Fig. 2, the experimental setup was established to measure the volume and temperature of the generated oxygen gas. Water substitution method was used to remove the effect of the water vapor. The volume and the temperature of the oxygen gas was measured with respect to the amount of the reacted H_2O_2, from 0.1ml to 0.15ml and 0.2ml. Each case, the experiment was repeated for 20 times, and we averaged the measured volumes and the temperatures. By substituting the measured temperature to (2), the theoretical oxygen volume is estimated and compared to the experimentally measured volume in Fig. 3. The measured volume is always lower than

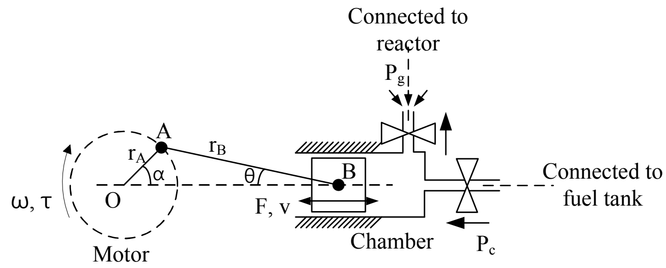

Fig. 4. The designed piston pump injection mechanism

the theoretical estimates, regardless of the amount of the reacted H_2O_2. The error between the experimental results and the theoretically estimated values were 11.3%, 5.60% and 6.27% for H_2O_2 of 0.1ml, 0.15ml and 0.2ml, respectively. It is inevitable results because the injected H_2O_2 was not perfectly decomposed into oxygen and water and 100% decomposition was assumed in theoretical estimation. Nevertheless, the experiment results for the relationship between H_2O_2 volume and O_2 gas show the similar tendency to the theoretical estimation. Therefore, the relationship in 2 was utilized for the design of the compact pneumatic power generator.

C. Design of Pneumatic Power Generator

Based on the reaction relationship in (2), the pneumatic power generator was designed as shown in Fig. 1. The piston pump driven by a low power consumption motor was developed to pump the H_2O_2 into the reactor. The pressure of the gas reservoir starts to rapidly increase by the operation of the piston pump, and this leads to the high back pressure at the outlet of the injector. For this reason, a powerful injection pump system is necessary to endure the high back pressure of the generated gas. Although there are several commercial pumps to resist the back pressure of 5∼6 bar, these pumps consume too much power (i.e., 20∼50W), which significantly reduces energy efficiency of the power generator. Therefore, we designed the piston pump with low power consumption, as shown in Fig. 4. The motor torque is transmitted to the piston via crank-slider mechanism. As the piston moves back and forth, the pump chamber volume increases and decreases. Due to the check valve installed at the inlet and outlet of the chamber, the chamber volume change creates pressure difference between the chamber and the fuel tank. When the piston moves backward, the chamber pressure decreases and the fuel flows into the chamber from the fuel tank. On the other hand, when the piston moves forward, the chamber pressure increases and the fuel in the chamber is injected to the reactor. From the static analysis of the proposed piston pump, the piston velocity, v, and piston output force, F, was represented in terms of motor speed ω, torque τ,

$$v = r_A\omega(sin\alpha + cos\alpha tan\theta) \quad (3)$$

$$F = \tau/r_A(sin\alpha + cos\alpha tan\theta) \quad (4)$$

where α, θ, and r_A are crank angle, the limb angle, and length of the limb, respectively.

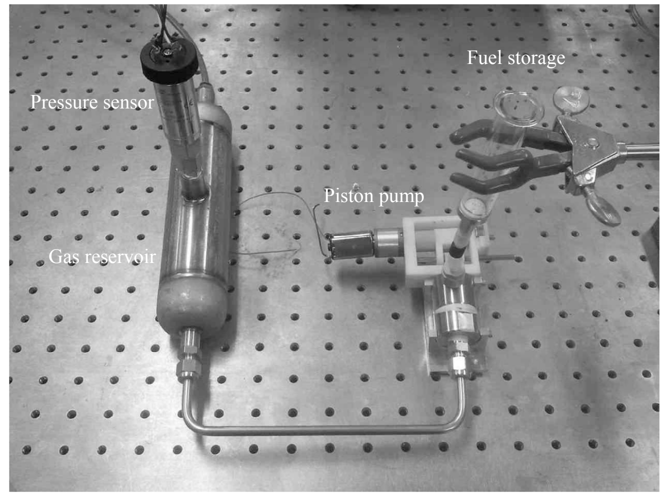

Fig. 5. The designed pneumatic power generation system

TABLE I
THE SPECIFICATION OF THE PNEUMATIC POWER GENERATOR $ ROBOT FINGER

Components	Specifications
Piston pump weight (kg)	0.4
Piston pump dimension (mm)	35L × 20W × 20H
Piston pump driving motor	IG-22GM,1/104, D&G Motor
Pressure Transducer	A5073, GE
Gas reservoir volume (ml)	200
Pneumatic power generator material	SUS304
Robot finger dimensions(mm)	154L × 14W × 15H
Robot finger DOF	1DOF (under-actuated)
Pneumatic actuator	DFK-10-50P (21g), Festo
Encoder	AS5045, AMS
Controller	Atmega128L, Atmel

By using designed piston pump, a prototype of the meso-scale pneumatic power generator based on the decomposition of the H_2O_2 was developed as shown in Fig. 5. The desired pressure of the proposed pneumatic power generator was set to 5 bar because most of the conventional pneumatic actuators can resist up to 6∼8 bar pressure and are usually operated in the 3∼4 bar pressure. The piston pump driving motor was selected to fulfill the pressure requirement. To prevent the potential corrosion of the device by contacting the H_2O_2, the prototype was developed by the stainless steel(SUS304). The specifications of the pneumatic power generator are given in Table. I. Feasibility test was performed to observe the performance of the system, and the experimental results are given in Fig. 6. The pneumatic power generator prototype created 4 bar pressure in 53.2 seconds, which is lower than the desired pressure. In fact, we assumed that the torque of the motor is perfectly transmitted to the piston without the friction of the other components such as O-ring, and it mainly results in the decrease of the pressure generation in real system due to the transmitted torque losses. On the other hand, the pressure generation rate decreased

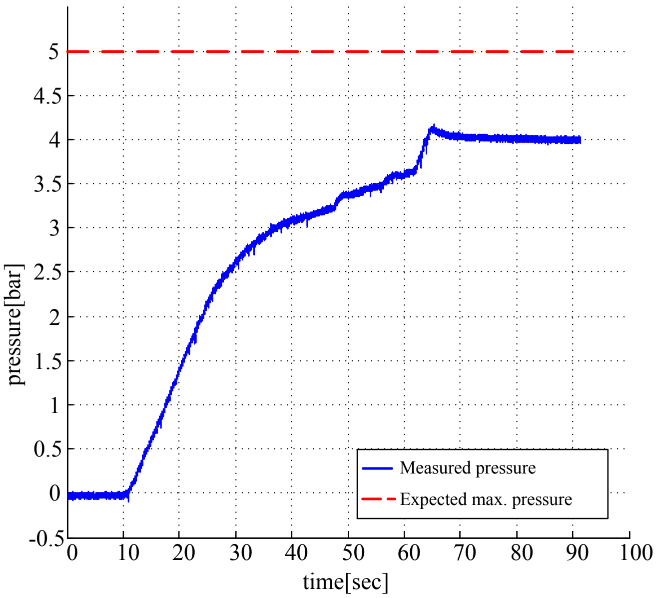

Fig. 6. Experiment result of Pressure generation

as the gas reservoir pressure increases by the back pressure applied to the piston pump have affected the performance of the pumping rate of the piston pump.

III. Robot finger powered by pneumatic power generator

A. Robot finger mechanism

By considering the design of the pneumatic power generator, a robot finger driven by the double acting pneumatic piston-cylinder actuator is designed as shown in Fig. 7. For the under-actuated mechanism, the robot finger adopts the four-bar linkage and seven-bar linkage structure connected by torsional spring. The seven-bar mechanism converts the linear motion of the piston to the rotation of the robot finger joints. In addition, four-bar linkage structure makes proportional movement between joint A and joint B as Eq. (5),

$$\theta_A = k\theta_B \tag{5}$$

where θ_A and θ_B represents bending angle of the joint A and joint B. In this paper, 4-bar linkage structure was designed to make k=1, which means joint A and join B rotate at the same angle. In addition, an under-actuated mechanism is realized for the shape-adaptive grasping. Fig. 7 shows the procedures to achieve the adaptive grasping during grasping tasks. That is, Link 3 only rotates before the robot finger contacts to the object, and when Link 3 contacts with the object, Link 1 and Link 2 gradually bend by increasing the pneumatic actuation force. Fig. 8 presents the overall view of the developed finger module, and the detailed specification of the developed robot finger is shown in Table. I.

B. Experiments

The prototype of the robot finger was powered by pneumatic power generator based on decomposition of H_2O_2 to

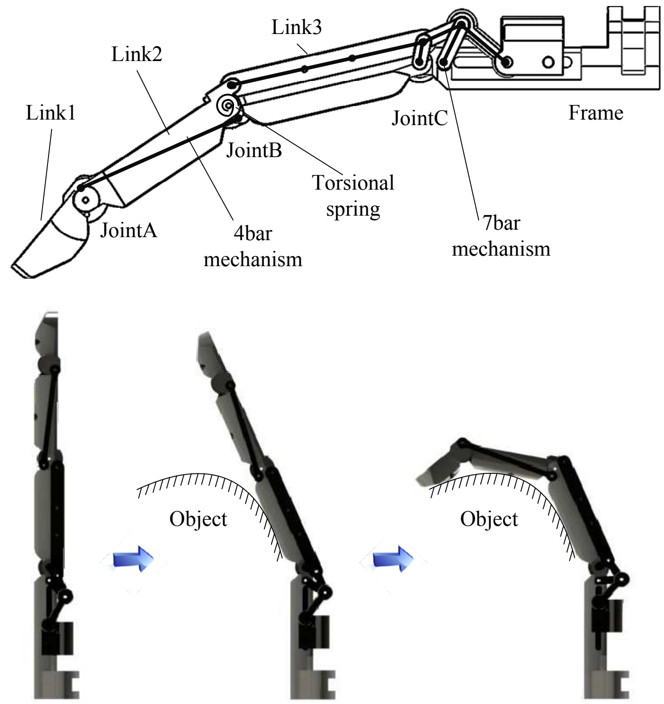

Fig. 7. Structure and bending procedure of the robot finger

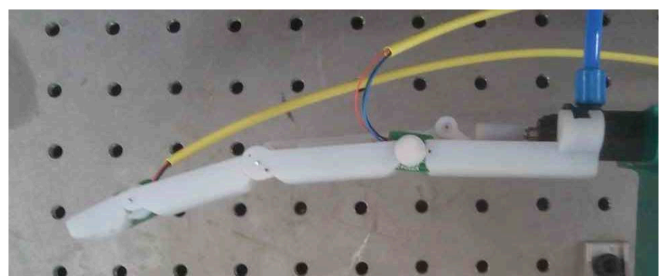

Fig. 8. The developed under-actuated robot finger

figure out the performances of the robot finger, such as fingertip force and joint velocity. The finger structure is fragile to high force or torque due to low yield strength of the rapid prototype material. Hence, we only supplied 2 bar pressure to the pneumatic actuator for the structural safety of the robot finger. The fingertip force was measured by loadcell and NT-505A indicator(CAS Corp.), as shown in Fig. 9. In addition, to measure the joint angles, we embedded the magnetic encoder(AS5045, Austriamicrosystems Corp.) at each joint. For this case, the angle of the joint A and joint C were measured because the joint A and joint B is coupled by 4-bar linkage mechanism. The open-loop controller was applied to manipulate the finger motion at 0.5Hz speed.

1) Robot finger performance: The measured joint angles are depicted in Fig. 10. By dividing the angle change with rise time, the angular velocities were calculated and described in Table. II. From the experiment, joint1 and joint2 rotated at 185deg/sec and joint3 rotated at 278deg/sec. In addition, 0.589N of the fingertip force was measured at 2bar pressure supply. By considering the piston force at 2bar

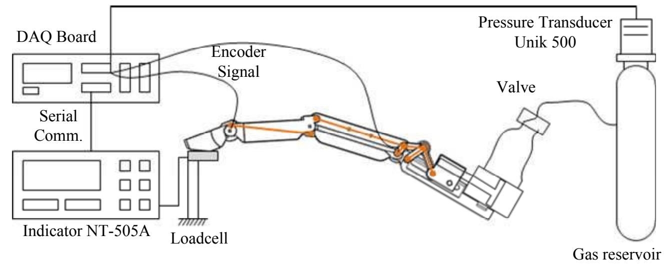

Fig. 9. Experiment setup used for performance measurements

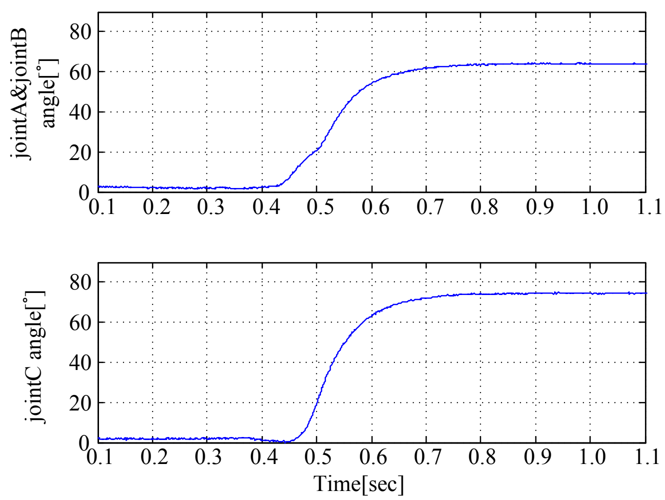

Fig. 10. Measured joint angles of the developed robot finger

pressure is 13.3N, the fingertip force was reduced to 4%. Note that the force reduction is mainly caused by the linkage structure used to transmit the piston force to the fingertip. While the piston moves only 20mm, the robot finger fully bends, by making all thres joint angle 90° . Since the output power of the system is always lower than the input power, the fingertip force reduces dramatically. Therefore the effective linkage structure should be considered to enhance the design.

2) Operation time of the robot finger: To generate the pressurized gas from the proposed system, we used 5ml of the H_2O_2, and it was stored in the gas reservoir. As shown in Fig. 11, the pressure of the generated gas reached up to 3.6 bar within 80 sec. In order to demonstrate the performance of the proposed system, we performed the consecutive flexion and extension motion of the robot finger at 0.5 Hz speed. The rate of the chemical reaction was feedback controlled to maintain more than the threshold pressure($P_{th} = 2$ bar) during the operation of the robot finger. Note that this control logic using two different threshold level is called the debouncing logic. Fig. 11 shows the experimental result for the operation of the proposed system. Until all the supplied hydrogen peroxide decomposes, we measured the pressure of the gas reservoir, and the operation time and the joint angle of the robot finger were also measured. It is shown that the robot finger was continuously operated for 60 seconds and 2 bar pressurized gas still remained in the gas reservoir.

TABLE II

THE PERFORMANCES OF THE ROBOT FINGER

Joint1&Joint2 velocity	Joint3 velocity	Fingertip force
185deg/sec	278deg/sec	0.589N

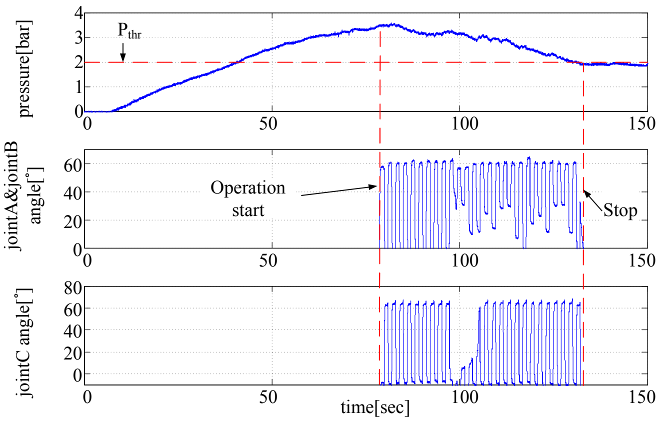

Fig. 11. Measured operation time using 5ml H_2O_2

Since the pressurized gas remained with 2 bar after the deactivation of the robot finger, the actual consumption of the H_2O_2 for the operation of the robot finger was less than 5ml. It implies that the proposed power generation system provides more than 1 hour operation of the mobile robotic systems by 300 ml H_2O_2.

IV. CONCLUSION

In this paper, a pneumatic power generator based on the decomposition of H_2O_2 was newly proposed to overcome the performance limitations of the current motor-battery system. Based on the chemical reaction property, we developed the compact piston pump for the injection of the H_2O_2. The piston-pump based on the crank-slider mechanism allows the remarkable reduction of the size and weight of the overall system. The designed pneumatic power generation system was applied to the under-actuated robot finger, and we observed the energetics of the pneumatic power generator and the performance of the robot finger. The energetics of the pneumatic power generator was identified by measuring the operation time of the robot finger for 5ml of the H_2O_2. As a result, the robot finger was continuously operated for 1 minute. However, the pressure generation rate of the proposed system was slow to supplement the pneumatic power consumption rate of the robot finger. In addition, joint velocity of the robot finger was measured to be 185deg/sec and 278deg/sec for joint A, B and joint C, respectively. Fingertip force of 0.58N was measured.

In the future, we will focus on the performance enhancement of the pneumatic power generator and the robot finger linkage mechanism.

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