# Pressure Control Valve for McKibben Artificial Muscle Actuators with Miniaturized Unconstrained Pneumatic On/Off Valves

Sumadi Jien, Shinichi Hirai, Yoichiro Ogawa, Masahiko Ito, and Kenshin Honda

*Abstract*— **The increased interest in wearable robots for rehabilitation and human assistance has also increased demands for lightweight and elastic actuators with inherent compliance for safe human-robot interactions. Although braided type McKibben actuators are frequently used as artificial muscles for robotic applications, they have two drawbacks. First, the weight and size of the necessary compressor and control valves limit the applications of these actuators as autonomous robots. Second, the control accuracy of these actuators is decreased by long tube connections that often cause pressure oscillations. This paper describes a pressure tracking controlled servo drive, using a McKibben actuator and miniaturized unconstrained on-off valves, which are smaller in size and easier to implement. The properties of unconstrained on-off valves are discussed, and different pressure control algorithms are compared. The pressure tracking control was also tested experimentally for its ability to track irregular waveforms at various pressure levels.**

## I. INTRODUCTION

The major advantages of pneumatic actuators are their high power to weight ratios and their inherent compliant behavior. Compliance is an important feature for human assistance or rehabilitation robots, which must interact safely with humans [1]. Among several types of pneumatic actuators, McKibben actuators are the most commonly used for human assistance robots, such as wearable robots, because they are extremely easy to assemble and can withstand a relatively high pressure ranges. Additional advantages of McKibben actuators include their low cost and weight, safe operation, and portability, increasing their potential to power wearable robots.

Applications using muscle-like McKibben actuators also require that the entire pneumatic system be portable. This include humanoid robots [2], [3], wearable robotics for rehabilitation [4], peristaltic locomotion within curving tubes [5], robotic hands [6], and autonomous hybrid microrobots [7]. The principle disadvantage of using pneumatic actuators is the hindrances caused by the weight and size of the bulky compressor, accumulator, and control valves. To ensure the mobility of a pneumatic system, high pressure $CO_2$ tanks [8] or DC-motor driven micro compressors are now utilized as air sources. Moreover, low-pressure and low-volume pneumatically actuated robots has been redesigned considerably to efficiently reduce the total size and increase the operation time [6]. The miniaturization of the driving valves is also important in achieving better volumetric energy density. Micro Electro Mechanical System (MEMS) valves are small in size, thus being potential candidates for driving low-pressurized pneumatic microrobots, although they are currently limited to high-pressure usages. New types of miniature high pressure valves are needed to augment the practicability of pneumatic actuators.

Despite difficulties in solenoid miniaturization, commercially available solenoid-actuated valves have been developed, but further miniaturization to micro size has been quite difficult. Our work on unconstrained on/off valves utilized a piezoelectric actuator that has high potential for downsizing. In addition, an unconstrained structure may make the valve assembly process easier, making it practical for miniaturization to the micro scale. Pneumatic on-off valves controlled by Pulse Width Modulation (PWM) are fundamental for the design of position/joint control and force/torque control. We previously described the performance of PWM-controlled unconstrained on-off valves [9]. Control using on-off valves is usually less expensive and more desirable than using servo valves. We have therefore assessed the feasibility of pressure tracking control using unconstrained valves, as well as to determine the most suitable control algorithms for the development of miniaturized unconstrained pressure control valves.

Section 2 of this paper describes the construction of a 3/3 Directional Control Valve (DCV) with unconstrained valves. Section 3 compares various pressure control algorithms in relation to the development of a miniaturized pressure control valve. Section 4 shows the experimental results of pressure tracking control and evaluation of control performance, and Section 5 presents our conclusions.

## II. 3/3 DCV WITH UNCONSTRAINED VALVES

In a pneumatic solenoid on-off valve, the flow rate is most commonly controlled by a controller that alters the PWM duty ratio command, while leaving the mechanical properties of the valves unchanged. There is no parameter in the mechanical components of solenoid valves that can be adjusted to control the output flow rate. In contrast, an unconstrained valve allows more flexibility in controlling the flow rate through the adoption of a piezoelectric actuator. Two additional parameters, input frequency and voltage, are available to adjust the output flow rate from the mechanical properties of unconstrained valves. Further descriptions of the input-output relationship of valves, as

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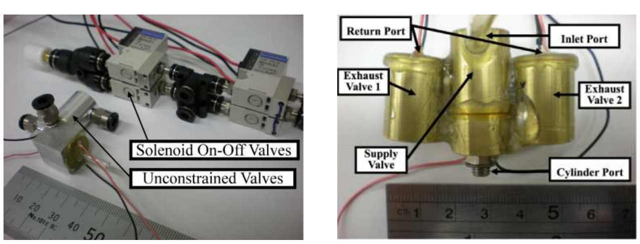
well as experimental results, have been presented in [9]. This distinguishing feature gives a considerable advantage to multi-level bang-bang controllers, which can save space and reduce the total weight by easily adjusting the flow rate as desired without having to incorporate more valves into the system [10]. Fig. 1(a) shows a comparison for multi-level hysteresis control between unconstrained control valves (with only 2 valves, measuring 35 x 25 x 15 mm) and solenoid on-off valves (with 4 valves, measuring 32 x 60 x 20 mm), making the volumetric ratio 1:3.

To control pressure with on-off valves, it has been suggested that the exhaust valves flow rate has to be at least 1.4 times greater than that of the supply valve [11]. A minimum of one supply and two exhaust valves are necessary to obtain the same response time to pressurize and depressurize a constant volume. As a general rule of thumb, multiple valves in parallel makes the charging/discharging response faster, although the weight and size of the pressure control valve will also increase. To limit the total size for the sake of miniaturization, a 3/3 unconstrained DCV is composed of one supply and two exhaust valves (Fig. 1(b)). The supply valve is $\phi$ 15 mm $\times$ 30 mm in size, and each exhaust valve is $\phi$ 15 mm $\times$ 20 mm, while the assembled 3/3 DCV unit measures 30 mm $\times$ 50 mm $\times$ 15 mm. Fig. 2 shows the input-output characteristics for supply and exhaust valves driving at a constant voltage of 20 V. To ensure operation in an autonomous robot, the valve could be driven by Ni-Cd batteries. If the supply valve switches on at a frequency 27 kHz and the exhaust valves switch on at frequencies of 16 and 14 kHz with all the valves switch off at frequency of 0 kHz, the charging and discharging outflow would be 17 L/min and 43 L/min, respectively (see Fig. 3(a)). Due to their unconstrained structure, the flow was rather unsteady when compared with a solenoid valve, which is commonly constrained. The unstable flow, however, had less influence on the pressure response (Fig. 3(b)). The amount of time required to pressurize and depressurize a 20 mL volume McKibben actuator is 770 ms, and is equal for the charging and discharging processes.




(a) (b)

Fig. 1. (a) Size comparison of 3/3 Directional Control Valve using unconstrained valves and solenoid on-off valves (b) Photograph of an Unconstrained 3/3 Directional Control Valve.

## III. MINIATURIZED PRESSURE CONTROL VALVE

### A. Pressure Control Circuit for Servo Drive

A schematic of a pressure control servo actuator and its control design architecture is shown in Fig. 4. A high-performance servo drive system was composed of a McKibben actuator (110 mm in length and 15 mm diameter bore), directly connected to a 3/3 DCV. The general objective of this section is to describe our design of a miniaturized lightweight pressure control valve using 3/3 unconstrained DCV for application to autonomous pneumatic robots. An MEMS pressure sensor (Panasonic ADP1181) was incorporated for feedback and it is necessary for the controller to be implemented with microprocessors.

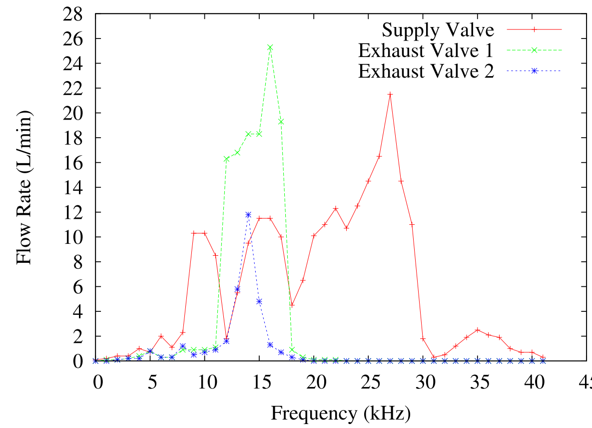
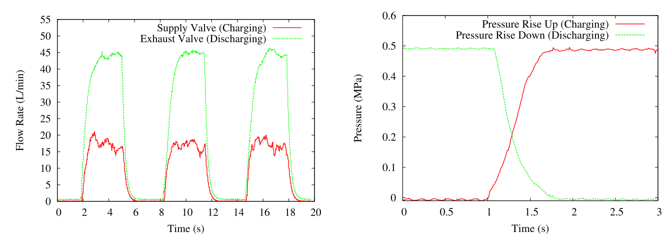



Fig. 2. Frequency flow rate relationship of supply and exhaust valves at 0.5 MPa and 20 V




(a) (b)

Fig. 3. (a) Supply and exhaust valves are switched on & off at a frequency of 0.1 Hz, a supply pressure of 0.5 MPa & an input voltage of 20 V (b) Response time to fill a 20 mL volume McKibben actuator, $\triangle p$ = 0.5 MPa.

### B. Pressure Control Algorithms

The most common pressure control technique for pneumatic systems with on-off valves is to modulate the PWM signal to control the flow. This type of control can also be attained by using a pulse code modulation (PCM) digital control valve driven by a series of on-off valves connected in parallel [12]. Since the weight and size of control valves can cause problems in autonomous robot, our aim was to develop a miniaturized pressure control valve, thus excluding the use of PCM control. The pressure control valve with 3/3 unconstrained DCV was used to drive a McKibben actuator. The tube connection between the valve and actuator was made as short as possible to improve the dynamic response, which leads to the realization of servo drive. In this context, the term servo drive indicates a pressure-controlled servo drive, and the position/rotational angle control is not discussed.

In pressure tracking control using solenoid on-off valves,

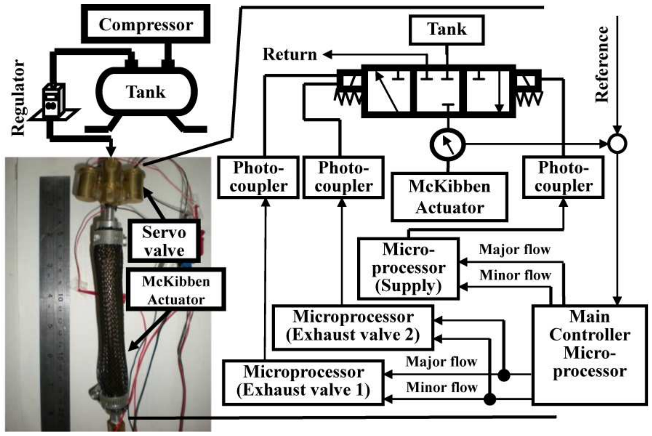



Fig. 4. Pressure control architecture of a servo drive with a McKibben actuator and controlled by (3-position) 3-way unconstrained DCV.

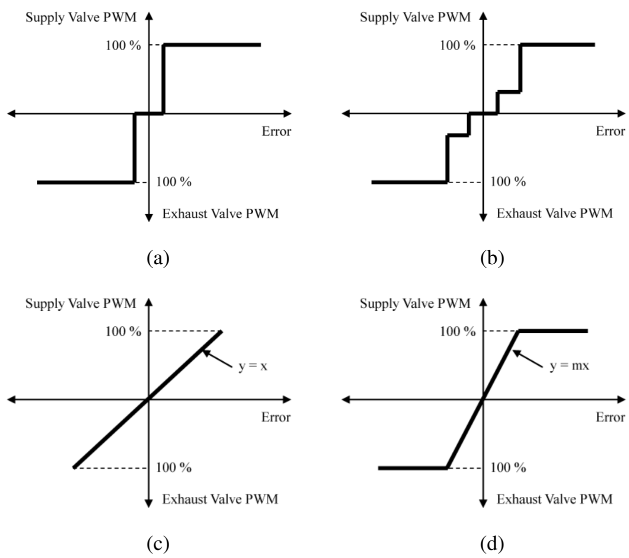



Fig. 5. Proposed pressure control algorithms for unconstrained on-off valves. (a) Hysteresis control, (b) Multi-level hysteresis control, (c) Proportional PWM control, and (d) Multimode switching: hybrid proportional PWM + bang-bang control

a low-level bang-bang controller with dead zone (hysteresis control) has been reported to be superior to a standard PWM controller [10], and a similar control method was implemented in the development of a small-sized pressure control valve [13]. To complement hysteresis control, we assessed four control algorithms (Fig. 5) to determine the most accurate pressure tracking control for unconstrained valves, where the error is defined as the difference between the reference setpoint and actual pressure.

## IV. Experimental Results

### A. Experimental Results of Pressure Control

The four control algorithms were experimentally compared to determine the most suitable pressure tracking control. Performance was assessed by comparative evaluation of tracking accuracy and stability. For evaluation purposes, both rectangular and sinusoidal waveforms were utilized to assess

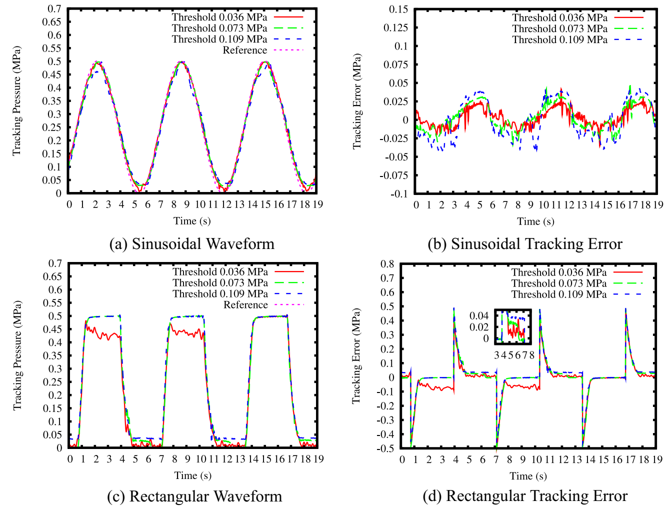
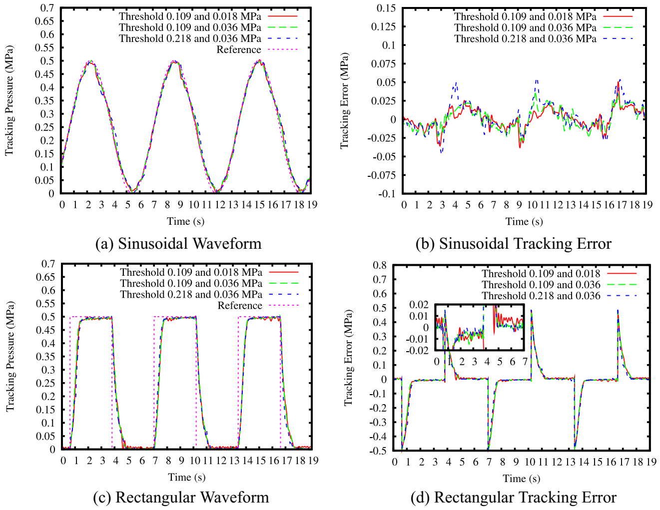



Fig. 6. Hysteresis control for tracking sinusoidal and rectangular input waveform at 0.1 Hz, input voltage 20 V, pressure 0.5 MPa

the characteristics of unconstrained valves. Control stability was obvious for rectangular waveforms, while tracking accuracy was more obvious for sinusoidal waveforms. The pressure tracking performance of each algorithm is described and discussed separately, and the algorithms are compared at the end.

*1) Hysteresis control:* This algorithm has only one control variable, *i.e.*, the dead zone threshold. Based solely on intuition, choosing too wide a dead zone threshold will worsen tracking accuracy while providing better stability. Similarly, a narrow dead zone threshold achieves better accuracy, but with tracking oscillations as a direct consequence. This control algorithm has a tradeoff between accuracy and stability associated with its simplicity. Fig. 6 compares three dead zone thresholds to show the limitation of this algorithm for tracking accuracy. Increasing the threshold to 0.036 MPa was accompanied by oscillations, showing that accurate and steady tracking is on the borderline between thresholds of 0.036 MPa and 0.073 MPa.

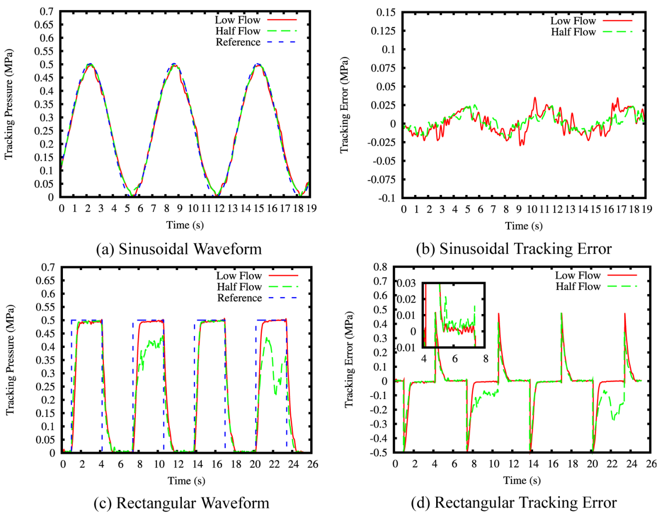
*2) Multi-level hysteresis control:* Multi-level hysteresis control was designed to compensate for the tracking error observed in hysteresis control. Three variables must be determined in this control algorithm: minor flow rate and inner and outer dead zone thresholds. Changes in outer and inner threshold are shown for 0.109 & 0.018 MPa, respectively; 0.109 & 0.036 MPa, respectively; and 0.218 & 0.036 MPa, respectively (Fig. 7). The major and minor flow rates were switched at 27 kHz($Q$= 21.5 L/min) & 6 kHz($Q$= 2 L/min), respectively, for the supply valve, 16 kHz($Q$= 26 L/min) & 10 kHz($Q$= 1.6 L/min), respectively, for exhaust valve 1, and 14 kHz($Q$= 12.5 L/min) & 8 kHz($Q$= 1.9 L/min), respectively, for exhaust valve 2. Our experimental results showed that multi-level hysteresis control improved tracking accuracy compared with hysteresis control. Similar to hysteresis control, if the threshold in multi-level hysteresis control is set relatively small, accuracy will increase but the system will suffer from oscillations.




(a) Sinusoidal Waveform (b) Sinusoidal Tracking Error

(c) Rectangular Waveform (d) Rectangular Tracking Error

Fig. 7. Multi-level hysteresis control for tracking sinusoidal and rectangular input waveforms of 0.1 Hz, input voltage 20 V, pressure 0.5 MPa



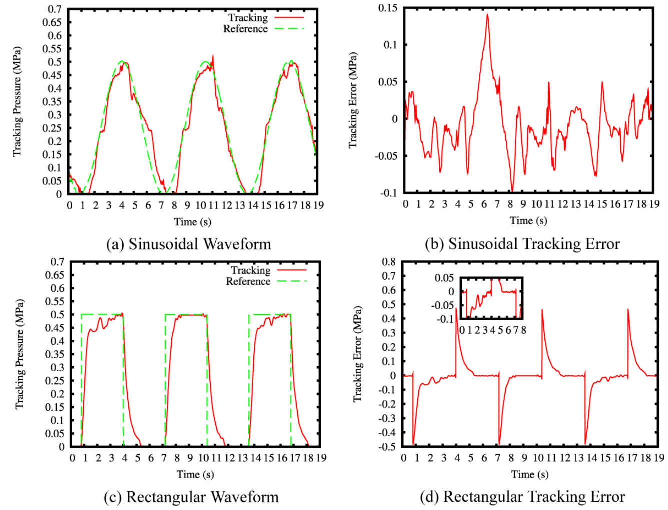

(a) Sinusoidal Waveform (b) Sinusoidal Tracking Error

(c) Rectangular Waveform (d) Rectangular Tracking Error

Fig. 8. Multi-level hysteresis control (threshold 0.109 & 0.036 MPa) for different levels of minor flow rate

The influence of minor flow rate was assessed by comparing two different minor flow rates, low and half flow rate, using the algorithm for threshold 0.109 & 0.036 MPa. Low flow rate refers to the above mentioned setting for minor flow rate, 6 kHz ($Q$= 2 L/min) for the supply valve, 10 kHz ($Q$= 1.6 L/min) for exhaust valve 1, and 8 kHz ($Q$= 1.9 L/min) for exhaust valve 2. Half flow rate refers to 22 kHz ($Q$= 12.3 kHz) for the supply valve, 12 kHz ($Q$= 17 L/min) for exhaust valve 1, and 13 kHz ($Q$= 6.5 L/min) for exhaust valve 2. At half flow rate, tracking accuracy was slightly increased for sinusoidal waveforms, whereas unstable performance was observed in tracking rectangular waveforms (Fig. 8). Thus, multi-level hysteresis control with thresholds of 0.109 & 0.036 MPa and low minor flow rate shows better performance.

*3) Proportional PWM control:* Because this control algorithm has a proportionally linear relationship between pressure difference and PWM duty ratio, there is no tran-




(a) Sinusoidal Waveform (b) Sinusoidal Tracking Error

(c) Rectangular Waveform (d) Rectangular Tracking Error

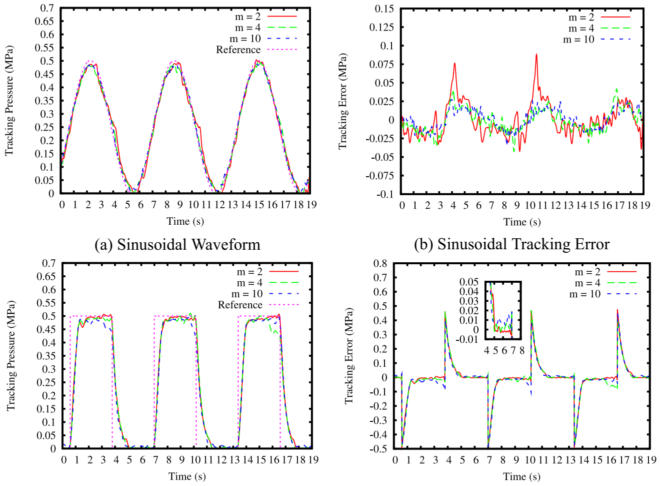
Fig. 9. Proportional PWM control for tracking sinusoidal and rectangular input waveforms of 0.1 Hz, input voltage 20 V, pressure 0.5 MPa

sient tracking error caused by a dead zone, as observed in hysteresis control. The major drawback of this method is sluggish response time, which may deteriorate into tracking inaccuracy (Fig. 9).

*4) Multimode switching control:* Bang-bang control is frequently described as time-optimal control but may be limited by the presence of transient errors. In contrast, although proportional control is time-sluggish, it may compensate for transient errors. Multi-mode switching control combines the advantages of both bang-bang and proportional control to derive a faster tracking response with better precision. This algorithm has only one variable, i.e., the gradient $m$ of a linear function $y = mx$. The experimental effects of gradient $m$ are shown in Fig. 10. Compared with proportional control, a proper determination of the gradient value may correct for tracking errors. The gradient value, however, has to be correctly chosen, otherwise it will lead to poor tracking performance.

### *B. Comparative Study*

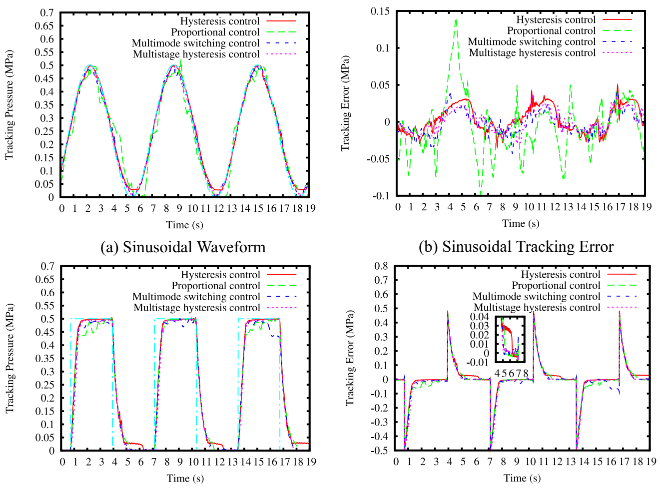
A representative of each control algorithm was selected based on assessments of best performance. The four control algorithms to be compared were determined from direct observations as hysteresis control, with a threshold of 0.073 MPa; multi-level hysteresis control, with thresholds of 0.109 & 0.036 MPa, with low minor flow rate, proportional PWM control, and multi-mode switching control with gradient $m$ = 4 (Fig. 11). Comparisons indicated that multi-level hysteresis control provided the best tracking control algorithm for both sinusoidal and rectangular waveforms, with a tracking error of 0.04 MPa for sinusoidal input and 0.0164 MPa for rectangular input (Table I). This results were similar to those of pressure control using solenoid on-off valves [10], [14]. Because unconstrained valves possess essential features of frequency-related adjustable flow rate, multi-level hysteresis control using unconstrained valves requires only three valves whereas solenoid on-off valves require about six valves.




(a) Sinusoidal Waveform (b) Sinusoidal Tracking Error

(c) Rectangular Waveform (d) Rectangular Tracking Error

Fig. 10. Multimode switching control for tracking sinusoidal and rectangular input waveforms of 0.1 Hz, input voltage 20 V, pressure 0.5 MPa




(a) Sinusoidal Waveform (b) Sinusoidal Tracking Error

(c) Rectangular Waveform (d) Rectangular Tracking Error

Fig. 11. Evaluation of pressure tracking control algorithms

TABLE I

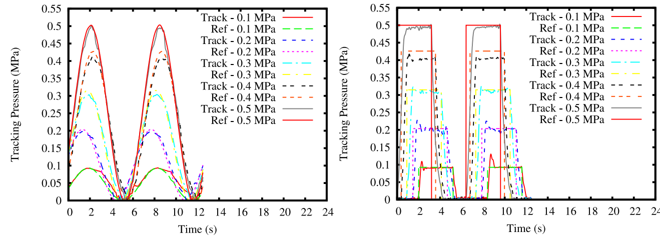
COMPARISON OF MAXIMUM TRACKING ERROR (UNIT IN MPA)

| Reference Input Waveform | Pressure Control Algorithms | | | |
|---|---|---|---|---|
| | Hysteresis | Proportional | Multimode switching | Multistage hysteresis |
| Sinusoidal | 0.0497 | 0.1407 | 0.043 | 0.04 |
| Rectangular | 0.0306 | 0.0541 | 0.0669 | 0.0164 |

Thus, the number of valves required can be halved, making the system more compact.

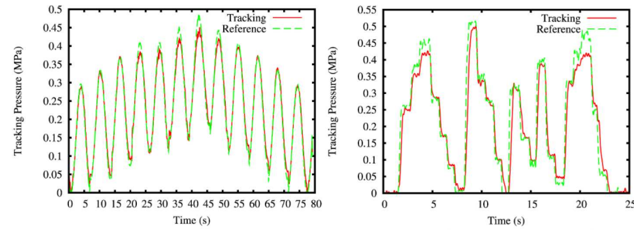
## V. PRESSURE TRACKING PERFORMANCE

To assess its trackability, transient stability and accuracy, pressure tracking control was evaluated at various pressure levels and irregular trajectories. Experimental results are shown in Fig. 12 and 13, with Fig. 12(a) and 13(a), respectively, showing that trackability of sinusoidal waveforms was satisfactory at high pressure but fairly inaccurate at low pressure. In tracking rectangular waveforms (Fig. 12(b) and 13(b)), we found that tracking performance was fairly good at high pressure, but quite poor at low pressure ranges. Large tracking errors for sinusoidal and rectangular waveforms at pressure 0.4 MPa may have been caused by unknown air flow characteristics that easily affected the unconstrained mechanism. Similarly, a study of pressure control using multi-port solenoid valves indicated that tracking errors can be canceled out by redesigning the control logic [13] & [15]. In addition, industrial-use proportional pressure control valves also overshoot when tracking a rectangular waveform [16], a finding frequently observed in pneumatic control systems. Compared with solenoid valves, unconstrained servo valves performed well, indicating that they were adequate for pressure tracking control.




(a) Sine 0.1 to 0.5 MPa (b) Square 0.1 to 0.5 MPa

Fig. 12. Multi-level hysteresis control (threshold 0.109 & 0.036 MPa) for tracking sinusoidal and rectangular input waveforms at 0.1 to 0.5 MPa, 0.1 Hz, input voltage 20 V




(a) Irregular Sinusoidal Wave Tracking (a) Irregular Square Wave Tracking

Fig. 13. Multi-level hysteresis control (threshold 0.109 & 0.036 MPa) for tracking irregular sinusoidal nd rectangular input waveforms at 0.1 Hz, input voltage 20 V, pressure 0.5 MPa

Fig. 14 shows sinusoidal responses for multi-level hysteresis control (threshold 0.109 & 0.036 MPa) at 0.05 Hz, 0.1 Hz, 0.25 Hz, 0.5 Hz and 1 Hz, respectively. Good tracking performance was observed until the phase started to fall off at around 0.1 Hz as shown in Fig. 15.

## VI. CONCLUSIONS AND FUTURE WORKS

This paper describes the implementation of a pressure servo actuator for McKibben actuators using piezoelectrically driven unconstrained on-off valves. Tracking performance was verified throughout using four control algorithms: hysteresis control, multi-level hysteresis control, proportional PWM control, and multimode switching control. We found that multi-level hysteresis control was superior to the other existing pressure control algorithms. Unconstrained on-off valves provide a controllable flow rate function that is advantageous for use in multi-level hysteresis control, where

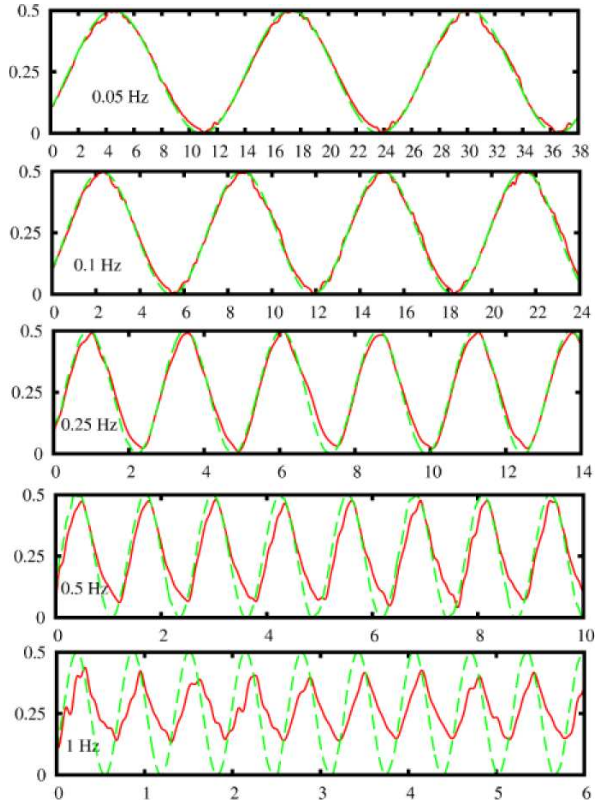



Fig. 14. Sinusoidal pressure tracking at 0.05 Hz, 0.1 Hz, 0.25 Hz, 0.5 Hz and 1 Hz with multi-level hysteresis control

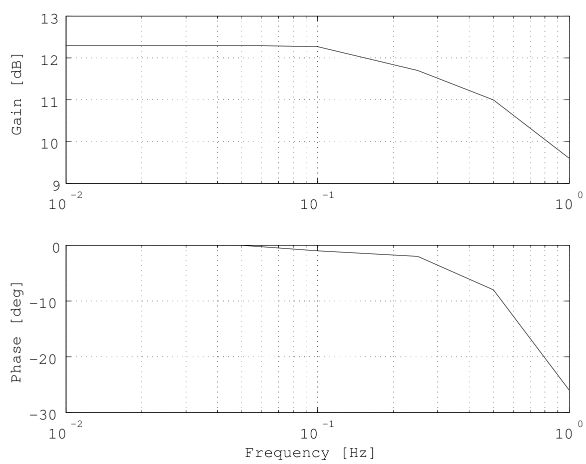



Fig. 15. Frequency response (bode plot) of multi-level hysteresis control

major and minor flow can be supplied by only one valve. As a result, the proposed system utilizes fewer valves and therefore has potential for miniaturization. Experimental demonstrations using irregular waveforms and different pressure levels indicate that this system has good tracking performance. Pressure control valves using unconstrained on-off valves are practically effective for wearable robots and human assistance robots.

Future work includes the further miniaturization of unconstrained servo valve for mini size McKibben actuators, as well as improvements in tracking performance. Future designs will address joint-angle control using unconstrained on-off valves placed in an antagonistic configuration to determine whether unconstrained on-off valves are practical for nonlinear control systems.

## VII. ACKNOWLEDGMENTS

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