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# Modeling and Control of a Miniature Servo Pneumatic Actuator

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***Abstract*** **– Pneumatic actuators are low-cost, safe, clean, and exhibit a high power to weight ratio. In this paper a novel servo pneumatic system based on a miniature cylinder with a 9.5 mm bore size is presented. Four low-cost 2-way proportional valves are incorporated to provide greater design flexibility than the traditional single 4-way servo valve solution. A nonlinear system model is developed and validated using open-loop experiments. The use of bipolynomial functions to model the valve flow rates provides a more accurate solution than the commonly used nozzle flow equations. A novel multiple-input single-output nonlinear position control law is designed using the backstepping method. The stability analysis includes the effects of friction modeling error and valve modeling error. In experiments with a 1.5 kg moving mass, the new control law produced maximum tracking errors of ±0.5mm for a 1 Hz sine wave trajectory, and steady-state errors within ±0.05mm. The tracking errors are 82% less than those produced by a linear controller.**

***Index Terms*** **– actuators, position control, pneumatic systems, nonlinear systems, Lyapunov methods.**

## I. Introduction

Pneumatic actuators continue to generate significant research interest due to their unique advantages. They are low-cost, safe, clean, and possess a high power to weight ratio. They have been successfully applied in rehabilitation [1], assistive devices [2, 3] and walking robots [4]. The lack of portability of their power source has also been addressed in recent research [5, 6].

In [5] solenoid injected monopropellant was used to power a 27mm bore pneumatic cylinder. The cylinder was controlled using two 2-way solenoid valves and one 3-way custom servo valve. The system was shown to be portable, and more energy efficient than battery-powered servomotors. A free piston pneumatic compressor was proposed as a mobile robot power source in [6]. Their preliminary experimental results demonstrate the promise of this device.

Improvements in pneumatic control were reported in [7-9]. In [7] a rodless cylinder with a 25mm bore was position controlled using a 4-way servo valve. Steady-state errors of 0.01mm and 1mm tracking errors were achieved for a range of payloads and operating conditions using a sliding-mode control algorithm. Independent stiffness and force control was demonstrated in [8] using a 27mm bore cylinder controlled by two 3-way proportional valves and a multiple-input multiple-output sliding mode controller. A similar setup was used to effectively implement impedance control in [9].

In the prior servo pneumatics research standard sized pneumatic cylinders were employed. Miniature sized pneumatic cylinders (with bore size less than 10mm) have not been studied. These cylinders possess the advantages listed above and are applicable to smaller scale applications in robotics, such as robotic hands and millirobotics. At the same time they are more challenging to control for two reasons. First, the seal friction is proportional to the bore diameter while the force generated by the air is proportional to the piston area. So as the bore size is reduced the ratio of friction force to piston force increases proportionally. Second, the chamber pressures and piston position are more sensitive to small variations in the mass flow rate so the flow rate behavior of the valves must be modeled precisely.

In this paper, the development of a servo pneumatic system based on a miniature cylinder is presented. The system structure and model derivation is described in Section II. A multiple-input single-output (MISO) nonlinear controller is designed in Section III. Experimental results are presented in Section IV. Conclusions are drawn in Section V.

## II. System Modeling

### *A. System Structure*

The system hardware is illustrated schematically in Fig. 1. The system includes a double-acting cylinder, and four low-cost 2-way proportional valves (labeled V1-V4). The valves have an input range of 0-5V. The cylinder has 9.5mm diameter bore, 3.2mm diameter rod and 25.4mm stroke. The four valves are interfaced through unity gain amplifiers to a PC via an analog/digital I/O board. The payload mass is mounted on a linear slide table. A linear variable displacement transformer (LVDT) position sensor is connected to the table to measure the displacement (see Fig.2). A pressure sensor is connected to each of the chambers of the cylinder. The sensors are also interfaced to the I/O board. The PC is programmed in C and a 1000 Hz sampling frequency is used.

The four valves allow the charging and discharging processes for the two chambers to be controlled independently. For chamber A, valve 1 controls charging from the supply and valve 2 controls discharging to atmosphere. With chamber B, valve 3 controls charging and valve 4 controls discharging. This valve arrangement increases the flexibility of the system.

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