Accurate Position Control of a Pneumatic Actuator Using On/Off Solenoid Valves

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Abstract—**The development of a fast, accurate, and inexpensive position-controlled pneumatic actuator that may be applied to a variety of practical positioning applications is described. A novel pulsewidth modulation (PWM) valve pulsing algorithm allows on/off solenoid valves to be used in place of costly servo valves. The open-loop characteristic is shown both theoretically and experimentally to be near symmetrical. A comparison of the open- and closed-loop responses of standard PWM techniques and that of the novel PWM technique shows that there has been a significant improvement in the control. A linear process model is obtained from experimental data using system identification. A proportional integral derivative (PID) controller with added friction compensation and position feedforward is successfully implemented. A worst case steady-state accuracy of 0.21 mm is achieved with a rise time of 180 ms for step inputs from 0.11 to 64 mm. Following errors to 64-mm S-curve profiles were less than 2.0 mm. The controller is robust to a sixfold increase in the system mass. The actuator's overall performance is comparable to that achieved by other researchers using servo valves.**

Index Terms— **Actuator, pneumatic, position control, pulsewidth modulation, solenoid valve.**

I. Introduction

PNEUMATIC actuators offer the following advantages for positioning applications: 1) low cost; 2) high power-to-weight ratio; 3) ease of maintenance; 4) cleanliness; and 5) a readily available and cheap power source. A particularly well-suited application for pneumatic actuators is the position control of robotic manipulators, end effectors, and grippers, where stiff and lightweight structures are critical. Unfortunately, pneumatic actuators are subject to high friction forces, deadband (due to stiction), and dead time (due to the compressibility of air). These nonlinearities make accurate position control of a pneumatic actuator difficult to achieve.

As a result, a considerable amount of research work has been devoted to the development of various position-control systems for pneumatic actuators [1]–[11]. Many of these systems, though successful, use expensive proportional servo valves and pressure sensor feedback loops. The objective of this paper is to implement inexpensive on/off solenoid valves, rather than servo valves, to develop a fast, accurate, and inexpensive pneumatic actuator system. A typical pneumatic servo valve may cost approximately $400 US, whereas a typical solenoid valve costs only $20 US, representing a 20:1 reduction in valve costs, or a savings of approximately 60% on the total cost of the pneumatic actuator. Also, servo valves tend to be bulky compared to compact and lightweight solenoid valves. However, with solenoid valves, fine motion control is difficult to achieve because of the limitation of the valve response time and its discrete on/off nature. Previous researchers [12]–[15] have tried to implement on/off solenoid valves for the position control of pneumatic actuators. These systems were successful in addressing smooth actuator motion in response to step inputs. However, some limitations still exist, such as positioning accuracy, minimum move size, and the ability to follow fast and accurately such trajectories as ramps and S-curve profiles. These issues will be addressed in this paper.

The paper begins with a discussion of the open-loop system design, including the hardware design and the design of the controller output signal. The process modeling is described, followed by the controller design. The control system performance is then verified experimentally.

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II. Open-Loop System Design

The objective of the open-loop system design was to design the hardware and controller output signal (i.e., the actuator input) to produce a system with the most linear input/output response.

A. Hardware Design

A schematic of the control system is shown in Fig. 1. A standard double-acting cylinder (152-mm stroke and 27-mm diameter bore) with a low friction option was selected as the actuator, to minimize the nonlinearities due to actuator friction. The actuator is connected to a horizontal linear slide, upon which different masses can be attached. Incorporated within the linear slide is a pneumatic brake mechanism which may be applied once the actuator has achieved the desired steady-state accuracy, locking it firmly in position. Two standard three-way solenoid valves are used with each cylinder. The valves were selected based on their low cost, fast response time of 5 ms, and high flow coefficient, $C_v = 0.10$. Flow controls were added to the cylinder inlets to increase the damping and filter out any significant vibrations caused by the pulsing of the solenoid valves. A linear potentiometer is used to provide position feedback, and its value is read by a 12-bit A/D converter. All control software is coded in "C" and is executed on an IBM PC. A photograph of the pneumatic actuator is shown in Fig. 2.