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Sliding mode control of a pneumatic muscle actuator system with a PWM strategy

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In this paper, a sliding mode control (SMC) strategy is applied to a pulse width modulation (PWM)-driven pneumatic muscle actuator system using high speed on/off solenoid valves. Servo-pneumatic systems with PWM-driven on/off valves can be used instead of expensive servo valves to decrease complexity, weight, and cost of servo-pneumatic systems. Due to the highly nonlinear nature of pneumatics, the system is difficult to model accurately which leads to un-modelled dynamics and uncertainties. In this paper, a robust and nonlinear SMC approach is implemented in order to control the system with sufficient accuracy. A nonlinear model is developed in a single-input single-output form by studying the flow, pressure, and force dynamics of the system. The SMC strategy is applied to three different system configurations: single on/off valve, two on/off valves, and a servo valve. The performance and effectiveness of these configurations are investigated under sinusoidal tracking at different frequencies. The robustness of the controllers is studied by varying the inertia of the system and by applying external disturbances to the system.

Keywords: pneumatic actuator; sliding mode control; solenoid valves; pulse width modulation

1. Introduction

Pneumatic systems have many properties that make them attractive for use in a variety of environments. They are less sensitive to temperature than hydraulic systems and it is not necessary to collect exhaust air which removes the need for fluid return lines. In addition, high force-to-weight ratios, cleanliness, compactness, ease of maintenance, and the safety of pneumatic actuators offer desirable features for many industrial designs. Pneumatic McKibben muscle actuators, invented by Gaylord (Gaylord, 1958), provide a higher force-to-weight ratio compared with pneumatic cylinders. However, there are a number of nonlinearities present that makes it rather difficult and complex to model effectively.

Nonlinear characteristics of the actuator, air compressibility, friction, and nonlinear airflow through the valves are the main reasons that pneumatic systems are commonly avoided for advanced applications. Literature demonstrates that a large number of control strategies have been proposed to handle the effects of the nonlinearities present. These include the following: PID control (Chou & Hannaford, 1996), adaptive control strategies (Caldwell, Medrano-Cerda, & Goodwin, 1995; Lilly J., 2003; Medrano-Cerda, Bowler, & Caldwell, 1995), nonlinear PID (Than & Ahn, 2006), neural networks (Hesselroth, Sarkar, Van der Smagt, & Schulten, 1994), and fuzzy controllers (Lilly J., 2003; Medrano-Cerda, Bowler, & Caldwell, 1995; Chan, Lilly, Repperger, & Berlin, 2003; Balasubramanian & Rattan, 2003). In (Lilly & Yang, 2005) and (Carbonell, Jiang, & Repperger, 2001), a sliding mode control (SMC) strategy was applied to a muscle actuator system, but only simulation results of the effectiveness of the strategy were presented. Other SMC approaches are presented in (Tondu & Lopez, 2000; Aschemann & Schindele, 2008; Shen, Nonlinear Model-Based Control of Pneumatic Artificial Muscle Actuator Systems, 2010). In (Tondu & Lopez, 2000), modelling and control of pneumatic muscle actuators in an antagonistic configuration for a 2-DOF SCARA-type robot prototype was studied. The system was controlled by a sliding mode control strategy based on an identified 2nd order model, from pressure input to joint angle. An additional integrative term in the close neighbourhood of desired angle position was used to improve the tracking accuracy. A static joint accuracy of $\pm 0.2^o$, and mean dynamic accuracy of $\pm 0.5^o$ for a trapezoidal velocity profile (0.5 rad/s cruising speed and a 0.5 rad/s^2 slope) was reported. In (Aschemann & Schindele, 2008), a cascaded SMC scheme was presented for a pneumatic linear actuator. A guided carriage was driven by a nonlinear mechanism consisting of a rocker with an antagonistic pair of pneumatic muscle actuators arranged at both sides. The differential flatness of the system was exploited in combination with sliding mode techniques to stabilize the error dynamics in view of un-modelled dynamics. The internal pressure of each pneumatic muscle was controlled by a fast underlying control loop. The control of the outer control loop involved a decoupling of rocker angle as well as mean internal pressure of both pneumatic muscles as flat outputs. Additionally, model uncertainties such as friction were directly counteracted by an observer-based disturbance compensation which

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