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Position Control of Hybrid Pneumatic-Electric Actuators

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Abstract – **The design, modeling and control of a novel hybrid pneumatic-electric actuator for applications in robotics and automation is presented. The design incorporates a pneumatic cylinder and DC motor connected in parallel. By avoiding the need for a high ratio transmission, the design greatly reduces the joint friction torque that contributes to the danger associated with robot arms. A novel discrete-valued model-predictive control (DVMPC) algorithm is proposed for controlling the position of the pneumatic cylinder with on/off valves, rather than costly proportional or servo valves. A variant of inverse dynamics control is proposed for the DC motor. A prototype was built for validating the actuator design and control algorithms. It is used to rotate a single-link robot arm. Experimental results are presented for vertical cycloidal and sinusoidal position trajectories. Even with the poor quantization caused by the on/off valves, the pneumatic cylinder controlled by the proposed DVMPC algorithm achieved a 2.5% maximum absolute error (MAE) for the vertical cycloidal trajectory. The DVMPC algorithm also switches the valves less often than the PWM method, reducing valve wear. With the addition of the DC motor to form the hybrid actuator, the performance improvement was significant. For the vertical cycloidal trajectory, the MAE was reduced to 0.37%. With the vertical sinusoidal trajectory, the MAE was 1.1%. These results compare favorably to the 5% MAE achieved by previous researchers for a horizontal sinusoidal trajectory using a hybrid pneumatic-electric actuator controlled by servo valves.**

I. Introduction

Electric motors are the most common actuator used in robotics and automation applications because they are easy to control precisely, and easy to interface. For most applications, they must be used with a high ratio transmission to provide sufficient torque. For example, ratios of 70:1 or more are typically used for driving the joints of a robotic arm. The resulting large friction torque may lead to serious injuries when collisions with the arm occur. This is true even when the motor is turned off. Compared with electric motors, pneumatic actuators are lower cost, provide a higher power to weight ratio, and are inherently safer due to the natural compliance of air. However, pneumatic actuators cannot attain the fast and precise position control possible with electric motors. A hybrid pneumatic-electric actuator offers the potential to combine the advantages of the individual actuators. If the actuators are connected in series the range of motion and positioning precision can be increased significantly, but the power output does not increase. If the actuators are connected in parallel, the power output, power to weight ratio, speed and positioning precision can all be improved. Furthermore, the large torque provided by the pneumatic actuator allows a low ratio transmission to be used with the motor so large friction torque is not a safety concern. For example, our hybrid actuator prototype has a static friction torque of 0.1 Nm, compared with 2.3 Nm for an industrial robot motor and transmission with a similar maximum continuous output torque (further details are provided in Section V.B).

The control of pneumatic actuators has been studied extensively (e.g., [1]–[16]). In this paper on/off solenoid valves will be used since they are much less expensive than proportional/servo valves (e.g., U.S.$40 vs. U.S.$800). They have the disadvantage that their control is discrete-valued, making smooth and precise actuator control difficult to achieve. Pulse-width modulation (PWM) [2], [6], [7], [15]; sliding-mode control (SMC) [1], [9]; and model-predictive control (MPC) [15]–[16] strategies have been used with on/off valves to improve closed-loop performance. Typically, MPC and SMC switch the valve less often than PWM resulting in longer valve life.

In contrast to pneumatic actuators, very little research has been performed on hybrid pneumatic-electric actuators. The scope will be limited here to the design and control of parallel- connected actuators since that is the focus of our research. A design concept for a rotary actuator consisting of an electric motor connected to pneumatic rotary actuator (also known as an air motor) was proposed in a 1987 patent [17]. It was intended to solve the problems of electric motor overheating and low power to weight ratio for high payload applications. No evidence was found of a commercial device (or even a prototype) being produced. The patent discusses a control algorithm in qualitative terms only. The hybrid actuator design proposed in [18] is the most relevant design found in the literature. They connected a DC motor in parallel with a rotary pneumatic motor using a pair of gears. The output shaft drove a single-link robot arm via a second pair of gears. The hardware included two servo valves, an optical encoder on the output shaft, and two pressure sensors. They presented two control algorithms. For tracking a sinusoidal trajectory they designed a SMC strategy based on a linearized model of the hybrid actuator. For point to point (PTP) motion control they proposed a mixture of SMC and proportional plus derivative (PD) control. They included experimental results for step inputs (for PTP motion) and a 200^{o} peak-to-peak, 0.5 Hz, sinusoidal input. Compared with the air motor operating alone (under SMC), the hybrid actuator

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