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Position control of hybrid pneumatic–electric actuators using discrete-valued model-predictive control

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ABSTRACT

The design, modeling and position 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 mechanical impedance that can make collisions with conventionally actuated robot arms dangerous. A novel discrete-valued model-predictive control (DVMPC) algorithm is proposed for controlling the position of the pneumatic cylinder with inexpensive on/off solenoid 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. The actuator inertia and static friction torque values for the prototype were only 0.6% and 4%, respectively, of the values found for a comparable actuator from an industrial robot. Simulation results for position control of pneumatic actuators with different valve speeds and friction coefficients show that the DVMPC algorithm outperforms a sliding mode control algorithm in terms of position error and expected valve life. Experimental results are presented for vertical rotary cycloidal trajectories. Even with the poor quantization caused by the on/off valves, the pneumatic cylinder controlled by the proposed DVMPC algorithm achieved a 0.7% root mean square error (RMSE) and a 0.25% steady-state error (SSE). With the addition of the DC motor to form the hybrid actuator, the RMSE and SSE were reduced to 0.12% and 0.04%, respectively. By incorporating a novel estimation algorithm, the system was made robust to an unknown payload.

1. 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, gear ratios of 100:1 or more are typically used for driving the joints of a robotic arm. The addition of the large ratio gearbox produces an actuator with high mechanical impedance (also known as a non-backdrivable actuator). This produces large contact forces when collisions with the arm occur, potentially causing serious injuries. Furthermore, a high impedance actuator cannot be used for precise force control unless an expensive force sensor is employed. The high impedance has two main causes. First, the moment of inertia at the output of the gearbox (known as the reflected inertia) is equal to the motor's inertia times the gear ratio squared. Second, the actuator's friction torque equals the motor's friction torque amplified by the gear ratio, plus the friction torque introduced by the gears. A further disadvantage of electric motors is that they are prone to overheating when they must provide a large continuous torque. Compared with electric motors, pneumatic actuators are lower cost, provide a higher power to weight ratio, do not overheat, and are inherently low impedance 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, and eliminate the disadvantages, 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 gear ratio to be used with the motor so the actuator's impedance remains low.

The control of pneumatic actuators has been studied extensively (e.g., [1–11]). In this paper, on/off solenoid valves will be used since they are much less expensive than proportional/servo

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