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Design and implementation of a new sliding mode controller on an underactuated wheeled inverted pendulum

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Abstract

In this paper, a sliding mode controller (SMC) is proposed for control of a wheeled inverted pendulum (WIP) system, which consists of a pendulum and two wheels in parallel. The control objective is to use only one actuator to perform setpoint control of the wheels while balance the pendulum around the upright position, which is an unstable equilibrium. When designing the SMC for the WIP system, various uncertainties are taken into consideration, including matched uncertainties such as the joint friction, and unmatched uncertainties such as the ground friction, payload variation, or road slope. The SMC proposed is capable of handling system uncertainties and applicable to general underactuated systems with or without input coupling. For switching surface design, the selection of the switching surface coefficients is in general a sophisticated design issue because those coefficients are nonaffine in the sliding manifold. In this work, the switching surface design is transformed into a linear controller design, which is simple and systematic. By virtue of the systematic design, various linear control techniques, such as linear quadratic regulator (LQR) or linear matrix inequality (LMI), can be incorporated in the switching surface design to achieve optimality or robustness for the sliding manifold. To further improve the WIP responses, the design of reference signals is addressed. The reference position for the pendulum is adjusted according to the actual equilibrium of the pendulum, which depends on the size of the friction and slope angle of the traveling surface. A smooth reference trajectory for the setpoint of the wheel is applied to avoid

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abrupt jumps in the system responses, meanwhile the reaching time of the switching surface can be reduced. The effectiveness of the SMC is validated using intensive simulations and experiment testings.

1. Introduction

Systems that have fewer control inputs than the degrees of freedom (DOF) to be controlled are defined as underactuated systems. Control of underactuated systems is a popular research topic due to its wide range of applications in robotics, underwater vehicles, aerospace vehicles, etc. [1,2]. From practical concerns such as cost reduction or weight reduction, many systems are designed to be underactuated. Some systems become underactuated when actuator failure occurs. As benchmark examples of nonlinear and underactuated systems, the cart-pendulum is often used to demonstrate and verify the effectiveness of control algorithms.

In recent years, the control of WIP systems has attracted attentions from both researchers and engineers. The well known commercial product, two-wheeled SEGWAY, is a popular personal transporter. For research and education purposes, prototypes of autonomous WIPs have been designed in universities and research institutes [3–9]. The WIP usually consists of two actuated wheels in parallel and an unactuated inverse pendulum. The control objective of the WIP is to perform position or velocity control of the wheels while stabilize the pendulum around the upright position that is an unstable equilibrium point. The WIP developed in [3–9] belongs to underactuated systems without input coupling [1]. The control input acts on the wheels only, while the balancing of the pendulum is achieved by the wheel motion. The mathematic model of the WIP system in [3–9] is essentially the same as that of the classic cart-pendulum system, therefore the control methods designed for cart-pendulum system can be directly applied to WIP system without input coupling.

Due to the difference in mechanical configuration, underactuated WIPs can be classified into the class without input coupling where the actuator is mounted on the wheel (class A), and the class with input coupling where the actuator is mounted on the pendulum or chassis (class B). Class A is more complex in mechanical construction but easier in controller design owing to the absence of input coupling. In contrast, class B is easier in mechanical construction but more challenging in controller design due to the input coupling between the wheel and the pendulum. Since the existing works mostly focus on studying control of underactuated systems without input coupling, this work is devoted to the development and control of a WIP with input coupling. When building the prototype of the WIP, the motor shaft coupler is fixed at the center of the wheels and the motor housing is rigidly connected to the inverse pendulum, thus the torque generated by the motor directly acts on both the wheels and the pendulum with the same size but opposite directions, which results in the input coupling of the WIP system.

Considering that various uncertainties exist in the WIP system, for instance, the joint and the ground frictions, the slope angle of the traveling surface, robustness is addressed in the control system design. SMC is a well known robust control approach for systems with model uncertainties and external disturbances and has been studied for control of wheeled inverted pendulum and similar underactuated mechanical systems [10–18]. SMC utilizes a discontinuous control law to drive system state trajectory into a designer specified

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