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# Subsystem backstepping design for controlling a class of nonlinear SISO systems with cascade structure

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ABSTRACT

This paper presents a controller design, referred to as the subsystem backstepping design (SSBD), for a class of nonlinear SISO mechatronic systems that comprise several cascaded subsystems. Compared with the conventional integrator backstepping design (CIBD) that deals with a first-order equation at each design step, the SSBD manages at each design step a subsystem that can be of high order. This both simplifies the design procedure and also makes controller parameters conveniently determined according to dynamic characteristics of each subsystem as in the conventional cascade control design with multiple feedback loops. However, in contrast to the conventional cascade control design, the SSBD does not require the inner feedback loop to respond much faster than the outer feedback loop, while guaranteeing system stability for a class of nonlinear systems. In addition, a variant of the SSBD, called internal model principle-based SSBD (IMP-SSBD), is presented to both further demonstrate the advantages of the SSBD procedure over the CIBD and also achieve robust tracking performance. The effectiveness of the proposed scheme is demonstrated through experimental studies of a harmonic drive system suffering from transmission compliance and periodic disturbances.



## 1. Introduction

Many important mechatronic systems are cascade systems, including magnetic levitation/bearing systems [1], electrical drives [2], flexible-joint electrically driven robots [3], electro-hydraulic/pneumatic systems [4], the RTAC (Rotational/Translational ACtuaor) and the TORA (Translational Oscillator with Rotational Actuator) [5]. For controlling such mechatronic systems, cascade control loops are often adopted to improve response characteristics of a single feedback loop. In a cascade control configuration, disturbances occurring in the inner loop are reduced or eliminated before their effects spill over to the outer loop. Thus, for cascade control to function appropriately, the inner loop must respond much faster than the outer one. Usually, the bandwidth of designed inner loop should be at least three times larger than that of the outer loop [6]. Cascade control has been a standard application provided by most industrial motion controllers due to its effectiveness and robustness [7]. Although such an engineering approach has been successfully applied in the industrial application [8], there are two main difficulties in using the cascade control. First, when the inner loop is severely limited by physical constraints such as control saturations and parasitic dynamics, the bandwidth of the inner loop cannot be tuned high, restraining the dynamics of the outer loop and leading to slow output responses. Secondly, the stability of the conventional cascade control systems cannot be easily ensured for nonlinear plants. In [9], a genetic algorithm was employed to determine cascade control gains for a nonlinear hydraulic servo system, which however does not guarantee the stability of the closed-loop system.

Despite the successful applications of cascade control, there is a lack of rigorous supports clarifying its stabilization capabilities for nonlinear systems. On the other hand, the conventional integrator backstepping design (CIBD) is a systematic approach to designing controllers that stabilize a vast class of nonlinear systems having a cascade or triangular structure. The CIBD is characterized by a step-by-step procedure that recursively designs a *virtual control* for a first-order state equation via a classical Lyapunov technique and "steps back" toward the control input. Starting with the first-order equation that is separated from the control input by a largest number of integrations, the CIBD obtains the true control expression at the final step. Compared with the conventional feedback linearization, it avoids cancellation of useful nonlinearities in pursuing the objectives of stabilization and tracking. However, since the CIBD deals only with a first-order equation at each design step, the design procedure is tedious for high-order systems. As shown in [1], the

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