Full-state feedback controller design with “delay scheduling” for cart-and-pendulum dynamics

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1. Introduction and problem statement

“Delay scheduling” is a recently introduced concept for time-delay system stabilization [8,9]. Assuming that a system has some unavoidable delays in the feedback line, which result in unstable dynamics, the answer to the following question is very critical: Is it possible to find some larger delay compositions that may recover the stability? The controller can obviously prolong the present delays, simply by introducing additional “hold buffers” in the feedback line. These extended delays may re-establish the stability; they may even introduce more attractive performance features. This concept of selectively increasing the delays is called the “delay scheduling” from which some counterintuitive results arise, as explained later in the text.

In order to deploy “delay scheduling” in a systematic manner, one needs to know the stability outlook of the system in the space of the delays. If we can declare the stable operating regions exhaustively for all possible delay compositions, this would describe the stability robustness of the system against uncertain but fixed time-delays as long as they remain within the stability regions. We can further argue that the delays can be time varying, and robustness would still hold, so long as the rate of change in delays is slow vis-à-vis the settling times of the system. We call this problem “the stability robustness against uncertain delays”. Without such a stability picture, it is not possible to perform the “delay scheduling”. For this we use a recent technique, called the Cluster Treatment of Characteristic Roots (CTCR) [1–6]. This technique reveals the complete set of delay compositions exhaustively where the stability is guaranteed.

The main idea behind the “delay scheduling” lies in the knowledge of the stability regions (pockets) in the domain of the delays. If a particular delay composition falls in the unstable operating region, we search for stable regions with larger delays (as the controller can increase but cannot reduce the existing delays). If there is only one single stable region and it does not contain the existing delay(s), can one redesign the controller to enlarge this region? Can one, then, increase the present delay(s) and improve the control performance? A practical strategy is needed to create such a controller and we propose one in this paper. This is the main contribution here, and it is experimentally verified using a fully-actuated cart–pendulum system (shown in Fig. 1), without loss of generality of the treatment.

The control objective for the experimental work is to make the two-degree-of-freedom cart–pendulum system track two respective desired trajectories. Two independent delays are considered in the two feedback lines. We propose a control synthesis methodology for this, which results in an enlarged stable region in the delay space. With the new control logic in place we schedule the delays for a stable operation.

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