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# Combined input shaping and feedback control for double-pendulum systems ☆

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ABSTRACT

A control system combining input shaping and feedback is developed for double-pendulum systems subjected to external disturbances. The proposed control method achieves fast point-to-point response similar to open-loop input-shaping control. It also minimizes transient deflections during the motion of the system, and disturbance-induced residual swing using the feedback control. Effects of parameter variations such as the mass ratio of the double pendulum, the suspension length ratio, and the move distance were studied via numerical simulation. The most important results were also verified with experiments on a small-scale crane. The controller effectively suppresses the disturbances and is robust to modelling uncertainties and task variations.

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## 1. Introduction

Double-pendulum systems are difficult to control when they are subjected to external disturbances. The control challenge is exacerbated by the difficulty of sensing the swing angle of the second pendulum. One of the most important classes of double-pendulum systems are those arising in crane operations. Cranes are highly flexible and lightly-damped systems. Manipulation of payloads can be challenging in the presence of swing induced by intentional motion of the crane and external disturbances, such as wind forces. The crane control system, which usually includes a human operator, must be robust to external disturbances. In addition, it must move the payload from one location to another with low settling time and minimal transient payload swing in order to achieve high throughput.

Input-shaping methods and feedback control have been developed and used for control of a wide range of flexible systems. Input-shaping is a type of Finite Impulse Response (FIR) filtering. It places zeros near the location of flexible poles of the system, leading to pole-zero cancellation [1,2]. The impulse amplitudes in an input shaper are determined by a set of constraint equations [3–5]. The command signal convolved with the input-shaper impulses suppresses unwanted excitation arising from intended motion. Numerous variations of this method have been demonstrated successfully to reduce payload sway on single-pendulum configurations [6–8], and on double-pendulum configurations [9–17].

Simulation based analyses of advanced input-shaping methods on double-pendulum cranes, and the capability to achieve negligible residual vibration due to induced motion by the actuator, are presented in [11]. Masoud and Alhazza [16]

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presented a frequency-modulation approach to tune the controller frequency such that a single mode input shaper can eliminate residual vibration in double-pendulum systems. Tuan and Lee [18] presented simulation based analyses of non-linear robust controllers using sliding mode control for sway reduction in double-pendulum cranes. Shah and Hong [19] suggested that modified input-shaping methods are also effective in mitigating residual oscillations in damped systems with external forces acting on them as observed in underwater fuel transport systems for nuclear power plants.

Feedback control methods have also been well studied, and implemented to reject external disturbances acting on cranes [20–22]. Blajer and Kotodziejczyk [22] presented a feedback based methodology for control of cranes while avoiding obstacles in a curvilinear path. The proposed methodology used precise path information and approximation of path using smooth splines to generate a feed-forward control law in combination with feedback control loop. These techniques can successfully reject external disturbances, but do not perform particularly well with motion-induced oscillations of the payload.

A combination of input shaping and feedback control is necessary for precise positioning of cranes subject to disturbances. A combination of feedback control and input shaping has been proposed for single-pendulum crane configurations [7,8,23,24], and benchmark mass-spring system [25]. Such controllers combine the benefit of both techniques and enable robust controller design. However, the previous work on the combined control methodology is limited mostly to single-pendulum configurations, and less effort has been directed at eliminating payload swing for double-pendulum crane configuration subject to external disturbances. Note that feedback control of double-pendulum cranes is very challenging because it is difficult to accurately measure the payload motion. In this work, the feedback loop is implemented based on the trolley position, and deflection of the hook which can be tracked from an overhead camera. The velocity command generated by the feedback loop is input-shaped to mitigate motion-induced vibrations.

In this work, a combined input-shaping and feedback controller is applied to double-pendulum bridge cranes. The system dynamics are described in Section 2. The mathematical model and controller implementation in simulation is described in Section 3. The experimental setup and results are presented in Section 4. The results from robustness analysis of the proposed method are discussed in Section 5. Finally, a summary is presented in Section 6.

## 2. System dynamics

Fig. 1 shows a schematic diagram of a planar double-pendulum bridge crane. The motors provide the actuation force for motion along the trolley direction. A cable of length $L_1$ is suspended below the trolley and supports the hook of mass, $m_1$. A rigging cable is attached to the hook, measuring $L_2$, and supports a payload of mass $m_2$. Assuming the lengths of cables to be constant, the governing linearized equations of motion are:

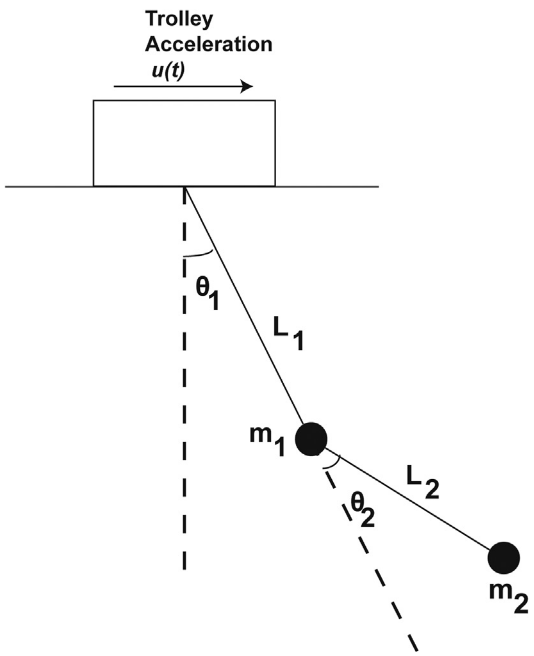


**Fig. 1.** Schematic diagram of a double-pendulum system.

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