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Practice article

Robust and novel two degree of freedom fractional controller based on two-loop topology for inverted pendulum

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ABSTRACT

A rotary single inverted pendulum (RSIP) typically represents a space booster rocket, Segway and similar systems with unstable equilibrium. This paper proposes a novel two degree of freedom (2-DOF) fractional control strategy based on 2-loop topology for RSIP system which can be extended to control the systems with unstable equilibrium. It comprises feedback and feed-forward paths. Primary controller relates the perturbation attenuation while the secondary controller is accountable for set point tracking. To tune the parameters of proposed fractional controller a simple graphical tuning method based on frequency response is used. The study will serve the outstanding experimental results for both, stabilization and trajectory tracking tasks. The study will also serve to present a comparison of the performance of the proposed controller with the 1-DOF FOPID controller and sliding mode controller (SMC) for the RSIP system. Further to confirm the usability of the proposed controller and to avoid the random perturbations sensitivity, robustness, and stability analysis through fractional root-locus and Bode-plot is investigated.

1. Introduction

Rotary single inverted pendulum (RSIP) fairly a distinct type of tunable mechanical oscillator is intrinsically nonlinear, underactuated, single input and multiple output system with unstable equilibrium point. These inherent characteristics present complications in controlling the system. Therefore, designing of a controller for the stabilization of pendulum is a challenging task. This design becomes more complex because of the physical limitations on applied voltage (V), the rotation angle (θ_1), pendulum angle (θ_2), and two sensor outputs. A prototype of RSIP shows similitude to the attitude control of a space booster rocket and a satellite, in which rocket assembly should be in a particular upright position and angle. The controlling function of RSIP is very similar to an underactuated robotic arm, stabilization of a cabin in a ship, aircraft stabilization in the turbulent air flow, walking of biped animals and robots, etc. The three key aspects investigated in the literature to control an inverted pendulum are as follows. The first aspect explains the swinging up of the pendulum from the original position to functioning position. Second is to stabilize the link of RSIP (balancing) at the unstable equilibrium point. The last aspect is tracking control of RSIP (tracing). Here the main focus is on balancing and tracking of RSIP, because of its wide utility in industrial applications.

Several control strategies have been reported in the literature to design a controller for stabilizing RSIP at unstable equilibrium point such as sliding mode control, advanced nonlinear approaches, fuzzy based compensation, linear feedback stabilization, and conventional type controllers etc [1–3]. All such designs require complex computations owing to their complex structure. Conventional PID (1-DOF) controller has been broadly used and known for an efficient solution to improve the transients as well as steady state performance of RSIP. It is transpired in the recent years that with the mathematical tools of fractional calculus (FC), numerous phenomena of engineering and other sciences even finance and social sciences are defined very effectively [4–7]. The necessity of defining a differential operator with an arbitrary order (real, fractional or complex order) is the reason behind the growth of FC. FC provides surplus flexibility for effective treatment of the system for improved performance and stability. The peculiarity of FC in mathematics gives an opportunity to substitute the conventional PID with fractional order PID (FOPID) in the topology of two loop PID Controller. Podlubny [8] at first presented a FOPID controller with an improved shape of closed loop response in comparison to PID controller owing to its higher degrees of freedom. Indeed, FOPID is a generalization of traditional PID controller with two supplementary

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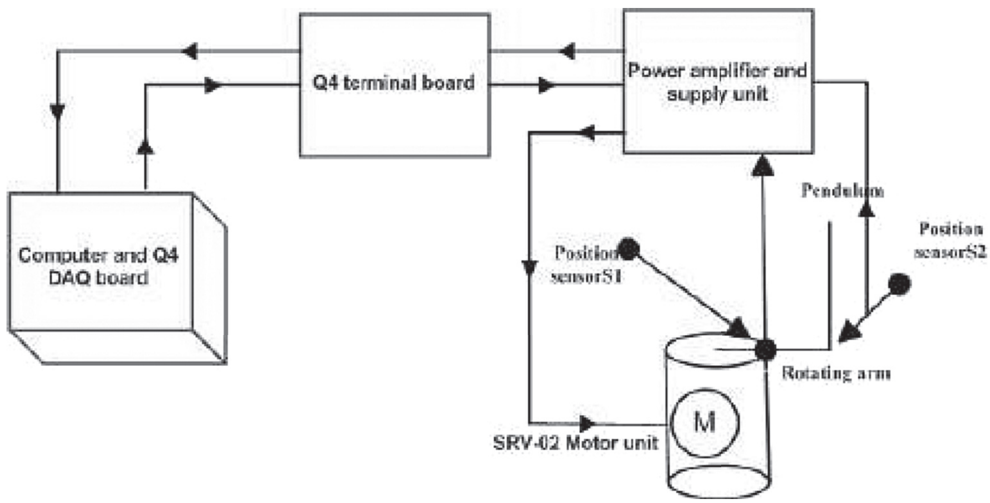

Fig. 1. Investigational setup.

tuning parameters, namely, fractional integrator order λ and a fractional differentiator order μ. Because of this advantage, design and performance analysis of a FOPID controller becomes a novel research topic for the researchers. Still, the performance of FOPID necessarily depends on the tuning procedure. Numerous tuning concepts have been noted in Refs. [9–11] to design a FOPID controller. However, the essential condition is to find out the more interesting specifications as per the requirement based on performance and robustness. Since the aim is to obtain a controlled system which should be robust to uncertainties of the plant model, load disturbances, and high frequency noise. Therefore, a graphical method based on frequency domain specifications is used for the design of fractional order controllers where all these constraints have taken into account.

Though, large overshoot is seen in 1-DOF FOPID controller because the design of 1-DOF comprises single feedback loop (set point-to-output transfer function) which is unable to ensure good tracking and perturbation rejection concurrently. As a remedy, another feed-forward loop (disturbance-to-output transfer function) as a pre-filter can blend with feedback FOPID controller for smooth set point tracking. The strategy 2-DOF FOPID controller boosts the disturbance rejection of the closed loop system while upholding the satisfactory set point response. 2-DOF FOPID controllers for different industrial plants were investigated by various authors in Refs. [12–15]. The objective is to apply a robust control for stabilization of pendulum link of RSIP based on 2-DOF technique. Here it is important to realize that a very wide range of design techniques already available in the literature. The main focus of this study is to minimize the deviation in rotational arm with the stabilization of a pendulum link in upright position. The additional problem is the disturbance rejection of the closed loop system at the time of sudden changes in reference input while upholding the satisfactory set point response. Therefore, this paper proposes the application of fractional calculus with an extra degree of freedom in loop robustness as an alternative option to solve such type of the control problems when dealing with physical applications. Here it is a need to mention that 2-DOF FOPID controller based on 2-loop topology is designed and tested on RSIP for the first time. No related literature is reported earlier.

The paper is organized as follows. Section 2 provides dynamics of RSIP. The design of proposed controllers and tuning method are provided in Section 3. Discussion and analysis of experimental results, comparison with 1-DOF and SMC controller, and robustness test for the proposed controllers are covered in Section 4. Section 5 presents the concluding remarks.

2. Rotary inverted pendulum

The inceptive inverted pendulum model was introduced as a cart type. However to compensate the limitation of the cart length, RSIP was invented [16,17]. The benchmark framework of RSIP is shown in Fig. 1. It is a nonlinear system having two degrees of freedom of

Table 1
Physical parameters of inverted pendulum.

Parameters Description	Notations	Experimental Value	Units
Viscous damping coefficient of arm	β_1	0.0024	N-m-s/rad
Viscous damping coefficient of pendulum	β_2	0.0024	N-m-s/rad
SRV-02 system gear ratio	K_g	70	–
Back emf constant	K_m	0.00767	V/(Rad/s)
Half-length of pendulum	l_2	0.1675	m
Mass of the pendulum	m_2	0.125	Kg
Rotating arm length	L_1	0.2159	m
Mass of rotary arm	M	0.2570	Kg
Armature resistance	R_m	2.6	Ω
Gearbox efficiency	η_g	0.9	–
Motor efficiency	η_m	0.69	–
Acceleration owing to gravity	g	9.8	m/s^2
Motor torque constant	K_t	0.00767	N-m/A
Moment of inertia of the SRV02 motor	J_{eq}	0.0035842	kg-m^2

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