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Article

Control of Linear Servo Carts with Integral-Based Disturbance Rejection

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Abstract: This paper describes a system designed for linear servo cart systems that employs an integral-based Linear Active Disturbance Rejection Control (ILADRC) scheme to detect and respond to disturbances. The upgrade in this control technique provides extensive immunity to uncertainties, attenuation, internal disturbances, and external sources of noise. The fundamental technology base of LADRC is Extended State Observer (ESO). LADRC, when combined with Integral action, becomes a hybrid control technique, namely ILADRC. Setpoint tracking is based on Bode's Ideal Transfer Function (BITF) in this proposed ILADRC technique. This proves to be a very robust and appropriate pole placement scheme. The proposed LSC system has experimented with the hybrid ILADRC technique plotted the results. From the results, it is evident that the proposed ILADRC scheme enhances the robustness of the LSC system with remarkable disturbance rejection. Furthermore, the results of a linear quadratic regulator (LQR) and ILADRC schemes are comparatively analyzed. This analysis deduced the improved performance of ILADRC over the LQR control scheme.

Keywords: Pole placement; ADRC; Active disturbance rejection; robust control; linear servo cart system

1 Introduction

As industrial systems become more complex, their analysis and control become even more complex, thus increasing the complexity. Recent research focuses on designing control systems robust to uncertainties that are internal like dynamics or external like disturbances. Some advancements in the research mentioned above are discussed as follows. First is the scheme to control the external uncertainties of linear/nonlinear systems using sliding mode control [1,2]. Next comes the scheme to control parameter uncertainties on interval systems using linear matrix inequalities [3,4]. Another method uses data-driven control to control online parameter identification and ultra-local models [5,6]. Finally, control of generalized disturbance, which controls both internal and external disturbances, is the ESO scheme proposed in [7,8]. This method cancels the generalized disturbance by deploying a feedback loop. These research advancements provide good enough samples for experimental and simulation results [9,10].

It is concluded that when parametric uncertainties and system nonlinearities are present, linear control schemes such as linear quadratic regulators (LQRs) and proportional integral derivatives (PIDs) exhibit instability. [11]. This raised the need for nonlinear control schemes like Fuzzy Logic control [12,13], and Neural Networks control [14], which were effective with improved convergence. Control of sliding mode systems (SMC) [15–17] is an effective and robust control method widely regarded for its ability to filter out disturbances. Nonlinear Dynamic Inversion (NDI) is another robust control technique competent in eliminating nonlinearities [18]. In order to effectively control the speed and position of a linear servo-cart system, state space-based fractional order integral controller is a powerful system technique [19–24].

LADRC control method solves both the setpoint tracking (SPT) and disturbance rejection (DR) problems more effectively than the standard method by accepting the disturbance as a variable [25]. The integer integrator is implemented to utilize this LADRC control for integral-based controllers. For such a controller, calculating the parameters of a non-integer fractional-order operator is very tough to achieve. This could be solved by the pole replacement method; however, the solution is still unsure [26]. The uncertainty is overcome by using augmented models for this controller [27,28]. State space-based fractional order integral controller is an augmented system technique for effective control of speed and position of a linear servo-cart system [25–27]. Calculating the control law parameters is then possible with a suitable pole placement. In addition, two aspects must be considered in this procedure. A first problem is that the CL reference model does not calculate the control law's non-integer order.

In addition, it must be logical. Secondly, the specific polynomial that corresponds to the augmented model has a high order. Finally, this proposed work plays a significant role in the following:

- Introduces the BITF model to control systems using integral-based controllers by imposing iso-dumping property in the CL response.
- Proposes the LDARC control for necessary action with the SPT loop.
- Contributes theoretically in designing a new control method for SPT controller using BITF.
- Validates the theoretical contribution by simulation results, especially concerning SPT controller gain variations, to robustizing the control structure.
- Implements the proposed ILADRC controller experimentally on a linear servo cart system. It is also more robust than the existing methods based on the results obtained.

Although there are many works on dynamic inversion-based controller algorithms, most of them integrated it with different other techniques and applied them to various applications. None of the investigations integrates with fractional-order control techniques as in our paper.

2 Problem Formulation

When designing a controller, the stability of the dynamical systems is the essential criterion. It is a well-known fact that model uncertainties and disturbances could cause instability to the system. For this reason, studies of new or improved controllers have continuously been an active research area. A linear servo cart system with a DC motor connected to a rack and cart is described in this article as an example of a dynamical system. The Fig. 1 shows the dynamical system described in this article as a linear servo cart. As the mass of the cart is one of the critical parameters in the system's dynamic, applying loads with different masses to the cart could change the system's dynamic. A practical example is when an additional load is applied to the cart when it is already in the desired position. The cart will oscillate because a bad controller will not compensate for changes in dynamic.

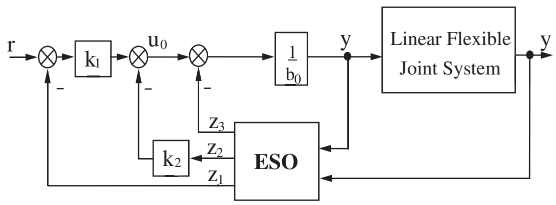


Figure 1: Standard structure of LADRC

There are many types of controllers introduced to overcome the mentioned issues. The RGDI controller has shown good setpoint tracking performance and robustness in dealing with system uncertainties in a similar application. However, there are still some tracking errors that we believe our proposed invention could improve, and there was also no proof if the RGDI can still perform well when disturbances are injected. Therefore, in this article, we will add a test where a disturbance is injected at a steady state and compare the performance of RGDI with our proposed invention.

3 Preliminary

The standard LADRC formulation for linear integer order systems does not require the control of the entire model. According to this method, the model's gain and degree are the determining factors. For a second-order model, the controlled scheme is as follows:

$$y^{(2)}(t) = b_0\, u(t) + f(t) \tag{1}$$

Where $u(t)$ is the input and $y\,(t)$ is the output of the system. The external disturbance is described by $d(t)$ and $f\,(t) = f\left(t, y^{(i)}, u^{(i)}, d^{(i)}, d\right) + (b - b_0)\, u\,(t)$ is the disturbance in general, the system gain b is estimated as b_0.

By using an ESO, the LADRC method estimates the unknown. In cases where $f\,(t)$ is differentiable, the extended state space model of Eq. (1) is

$$\begin{cases} \dot{x} = A\,x + B\,u + E\,h \\ y = C\,x \end{cases} \tag{2}$$

where: $x = \begin{bmatrix} y & \dot{y} & f \end{bmatrix}^T, h = \dot{f}$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix}, E = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},$$

and $C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$.

ESO is structured as follows

$$\begin{cases} \dot{z} = Az + Bu + L\,(y - y_o) \\ y_o = Cz \end{cases} \tag{3}$$

where, L is the observer's gain vector.

$$L = \begin{bmatrix} \beta_1 & \beta_2 & \beta_3 \end{bmatrix} \tag{4}$$

Asymptotically stable $(A - LC)$ is obtained by determining the parameters parameters β_i, $(i = 1, 3)$. The variables $z_1\,(t)$ and $z_2\,(t)$ are approximated by the output $y\,(t)$, and its derivative, $\dot{y}\,(t)$, and $z_3\,(t)$ the variable, $f\,(t)$ is approximate. The control law is selected as follows in order to reject the estimated disturbance:

$$u\,(t) = \frac{u_0\,(t) - z_3(t)}{b_0} \tag{5}$$

Eq. (1) becomes two cascaded integer-order integral operators without considering the estimated error, $(z_3\,(t) = f\,(t))$.

$$y^{(2)}\,(t) = u_0\,(t) \tag{6}$$

As a standard solution to setpoint tracking, state feedback is used. Therefore, the control law $u\,(t)$ can be stated as follows:

$$u_0\,(t) = k_1\,(r\,(t) - z_1\,(t)) - k_2 z_2\,(t) \tag{7}$$

$r\,(t)$ represents the reference signal, k_1 and k_2 are the state feedback gains that impose the transient tracking of the setpoints.

LADRC's standard structure is shown in Fig. 1. The gain vectors to be designed for this system are the K_o for the controller, and the L for the ESO. The method that is generally used to design these gain vectors. The observer and controller bandwidths are determined by two parameters, ω_o and ω_c.

4 LADRC with Integral Action

The main point to bear in mind is that derivatives of non-integer order have different meanings, and that these definitions are not always equivalent. In this paper, we propose a control system based on a LADRC and integer-ordered necessary actions. The present study has combined fractional integrals with another technique. Specifically, its main objective is to enhance the performance of the standard LADRC for fuzzy systems, specifically regarding the effect of external disturbances. It was shown in Fig. 2 how the proposed technique works.

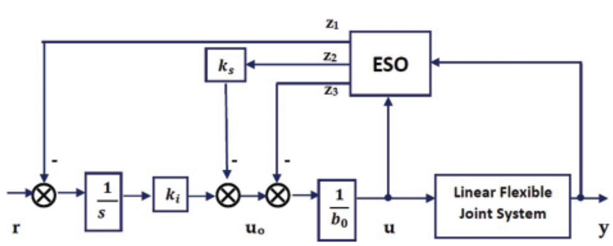


Figure 2: Integral control structure of LADRC

According to the state feedback K_s, the CL characteristic polynomial's n poles may be placed at their discretion. Eq. (9), in order to impose on the closed-loop Bode's ideal transfer function, is coupled with the fractional integration gain, K_i. Then the LADRC structure may be strengthened in terms of the open-loop gain setpoint. In this case, Eq. (3) indicates the ESO. Based on this, we have the following control signal:

$$u_0(t) = k_i \mathfrak{I}_\alpha (r(t) - z_1(t)) - k_{s2} z_2(t) \tag{8}$$

where $\mathfrak{I}_\alpha$ (.) denote the fractional-order integral operator [23,26].

The following would be a progression of methods that can be used to determine the coefficient of state feedback K_{s2}, the coefficient K_i associated with the fractional integrator of Eq. (8), and finally the non-integer order α of the fractional integrator of Eq. (9).

$$G_{cl}(s) = \frac{1}{(1 + Ts)\,\tau_c s^{\lambda+1} + 1} \tag{9}$$

This corresponds to the open loop

$$G_{ol}(s) = \frac{1}{(1 + Ts)\,\tau_c s^{\lambda+1}} \tag{10}$$

when $T \ll \tau_c$ has the same frequency characteristic, Bode's ideal transfer function exists [27,28].

Eq. (6) gives the equation for a closed-loop system with a control plant, and Eq. (8) gives the equation for the control law:

$$G(s) = \frac{k_i}{s^{\alpha+2} + k_s s^{\alpha+1} + k_i} \tag{11}$$

The following is a simple way to write it

$$G(s) = \frac{1}{\frac{k_s}{k_i} s^{\alpha+1}\left(1 + \frac{1}{k_s}s\right) + 1} \tag{12}$$

The transfer function in Eq. (9) has to have exactly the same value as the reference model in this equation.

$$\alpha = \lambda, \qquad k_s = \frac{1}{T}, \qquad k_i = \frac{1}{\tau_c T} \tag{13}$$

Remark: ω_c is replaced by the parameters τ_c and λ, and ω_0. In order to be compatible with standard LADRC, and ω_0 remains for the calculation of observer gains. For the observer to be able to calculate the generalized disturbance, one needs to know the magnitude of the disturbance. Therefore, the time constant T will generate a smaller frequency than ω_0.

5 Mathematical Modeling of LSC System

Fig. 3 depicts a typical LSC system. The LSC system consists of a DC motor and the gearbox, whose schematic diagram is shown in Fig. 4. M_c defines the mass of the cart and v_c its velocity. B_c, defines the viscous damping force which causes motor pinion of the cart; the two damping terms are added together to yield the equivalent damping factor, B_q. F. This coefficient is equal to the torque developed by the servo motor. Newton formulated his second law of motion in the following way:

$$\dot{x}_c = v_c \tag{14}$$

$$M_c \dot{v}_c (t) + B_q v_c (t) = F (t) \tag{15}$$

where,

$$B_q = \frac{\eta_g k_g^2 \eta_m k_t k_m B_c r_{mp}^2 R_m}{r_{mp}^2 R_m} \tag{16}$$

with the following factors,

η_g - the efficiency of the transmission,

kg - the ratio between the gears,

η_m - efficiency of the motor,

k_t - constant torque of the motor,

k_m- constant of the back-emf,

rmp - the motor pinion radius, and

Rm - motor resistance.

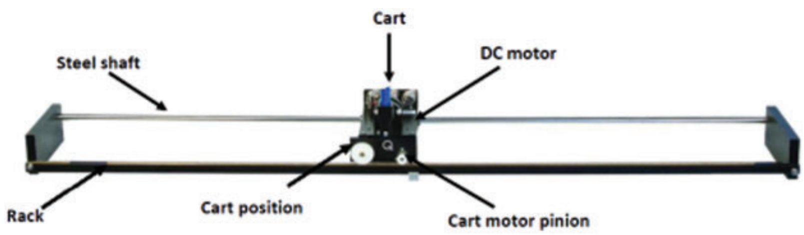


Figure 3: Cart system with linear servos

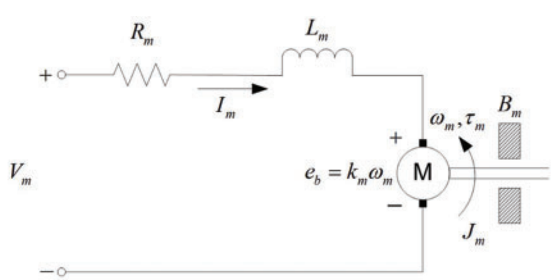


Figure 4: LSC system diagram

As a result of its low value, motor inductance is ignored.

The driving force,

$$F (t) = A_m v_m (t) \tag{17}$$

where v_m is the voltage applied to the actuator, and A_m represents the gain of the actuator, obtained as $A_m = \frac{\eta_g k_g \eta_m k_t}{r_{mp} R_m}$. Dynamics of cart speed vc is expressed in Eq. (15) and is directly affected by input voltage vm. This results in the transfer function as follow:

$$\frac{V_c(s)}{V_m(s)} = \frac{A_m}{M_c S + B_q} \tag{18}$$

The steady-state gain and time constant are derived from the above transfer function as $K = \frac{A_m}{B_q}$ and $\tau = \frac{M_c}{B_q}$, respectively. The following is the plant transfer function for the application of voltage to the cart:

$$P(s) = \frac{K}{\tau s + 1} \tag{19}$$

Eq. (15) does not account for inertial forces due to motor armature as described above. It is important to note that if this force is taken into consideration, it will only result in change to the time constant parameter, and not to the steady-state gain, such that

$$\tau = \frac{J_q}{B_q} \tag{20}$$

with equivalent inertia term calculated as follows:

$$J_q = M_c + \frac{\eta_q K_g^2 J_m}{r_{mp}^2} \tag{21}$$

The voltage and cart position transfer function can be computed through the cascading of an integrator (*1*/*s*) with the speed transfer function as,

$$P(s) = \frac{K}{s(\tau s + 1)} \tag{22}$$

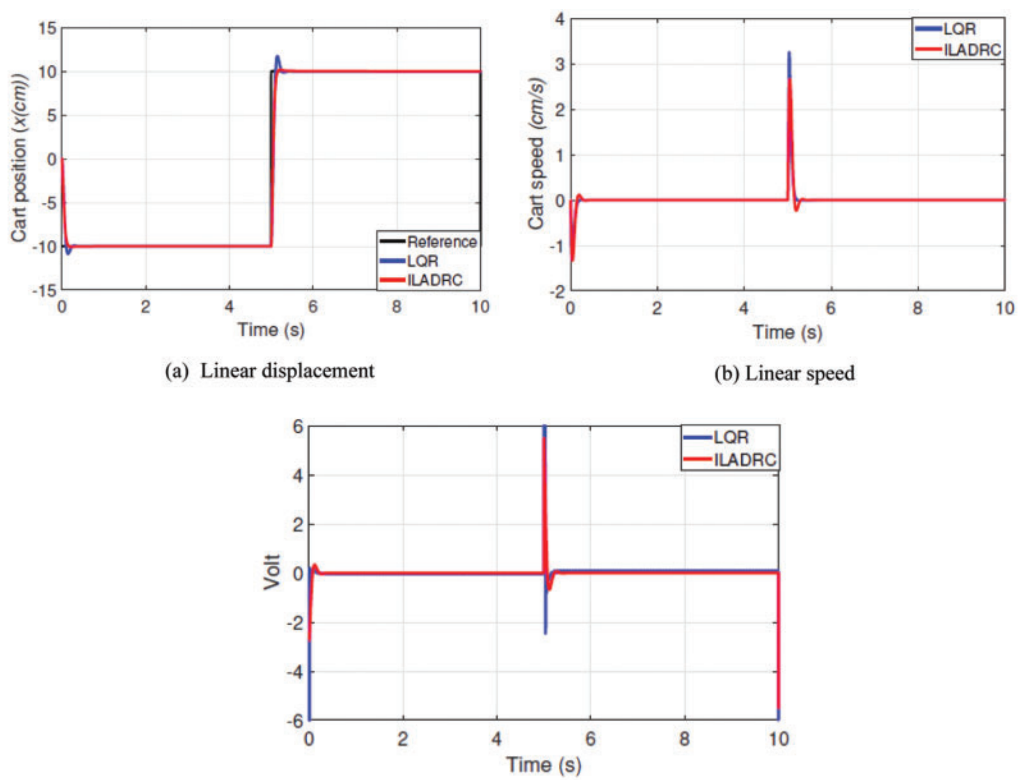
6 Linear Servo Cart Implementation

An example of LADRC control scheme that validates the performance of the proposed Integral based LADRC control scheme consists of a linear servo cart system, which consists of two carts sliding on a track and driving one of them using a DC motor. This system has been found to be an interesting example of a LADRC control scheme that utilizes a linear servo motor to drive one of the carts. Due to the interaction between two systems, the modeling of this system is complex. During testing, determining the cart's position was the objective, and the vibration was considered a permanent disturbance. As shown in Fig. 3, a linear servo cart system (LSC) is used. Fig. 4 illustrates this with a mass system in which m_c is the cart's mass, and x_c is the cart's position. The location of the cart is determined by a physical optical encoder. F_c denotes the linear force applied to the cart. The cart is propelled by a DC motor, which provides the necessary force for it to move. In place of a fixed controller, the motor voltage is used to control the cart whereas the position of the cart on the rail provides variable control. Matlab/Simulink implements the control law by interfacing the hardware with QUARC tools on a PC through the QUAC tools. QUAC tools sample the control law every 0.001 s. Control of the motor is done through the use of both digital and analog data acquisition devices, and specifically through the Q2 USB DAQ. In order for the command to be amplified (to be translated into motor voltage 24 V), an amplifier (VoltPAQ-X1) is employed.

To demonstrate the LQR control scheme and compare ILADRC's performance to the standard LQR structure, we use the linear servo cart system described above. A linear servo cart system is an interesting example since a DC motor drives a cart sliding on a track. Controlling the cart's position is the goal, and the uncertainty is regarded as a permanent disturbance.

Computer simulations are performed on a linearized Linear Servo Cart (LSC) system to authenticate the controller's performance to evaluate the real-time performance. In Simulink/Matlab, we create a simulation environment with a simulation time of 5 s in order to analyze numerically the controller performance. The square wave profile having an amplitude of 100 mm with a frequency of 0.66 Hz is commanded as a reference input command to the LSC system. The linear displacement and speed response and the controlled voltage to a reference square wave command are shown in simulation results.

The simulation is carried out by providing a square wave linear displacement profile with a magnitude of ± 10 cm with a frequency of 0.1 Hz. Fig. 5 compares different control approaches for a square input command. The performance indices in terms of rising time, settling time, and overshoot achieved through ILADRC control are better than its counterpart control strategies. The more significant overshoot and chattering phenomenon are visible in the LQR response. In contrast, no overshoot is observed in ILADRC response with faster convergence towards the reference command in the transient phase followed by smooth, steady-state performance. The time responses of the linear speed and corresponding controlled voltages undersupplied capacity are shown in Figs. 5b and 5c, respectively.



(a) Linear displacement

(b) Linear speed

(c) Controlled voltage

Figure 5: Square-wave tracking

The simulation was performed by considering a sawtooth profile as a reference input to the LSC system to visualize the performance of ILARDC with traditional LQR for robustness and parametric uncertainties. The evolution of the linear position and speed responses and controlled voltages are illustrated in Fig. 6. The time response curves of linear displacement against the sawtooth profile are shown in Fig. 6a. The results depict improved performance of ILADRC control as compared with LQR, by keeping the linear servo cart closer to the desired reference input command. The time-domain speed curves are shown in Fig. 6b. Finally, the controlled voltages of two control approaches are presented in Fig. 6c, in which the undesirable high value is observed in the controlled voltages generated by LQR, whereas these are significantly reduced by proposed ILADRC control. Therefore, from the results, it is concluded that ILADRC control demonstrates improved tracking control and better performance.

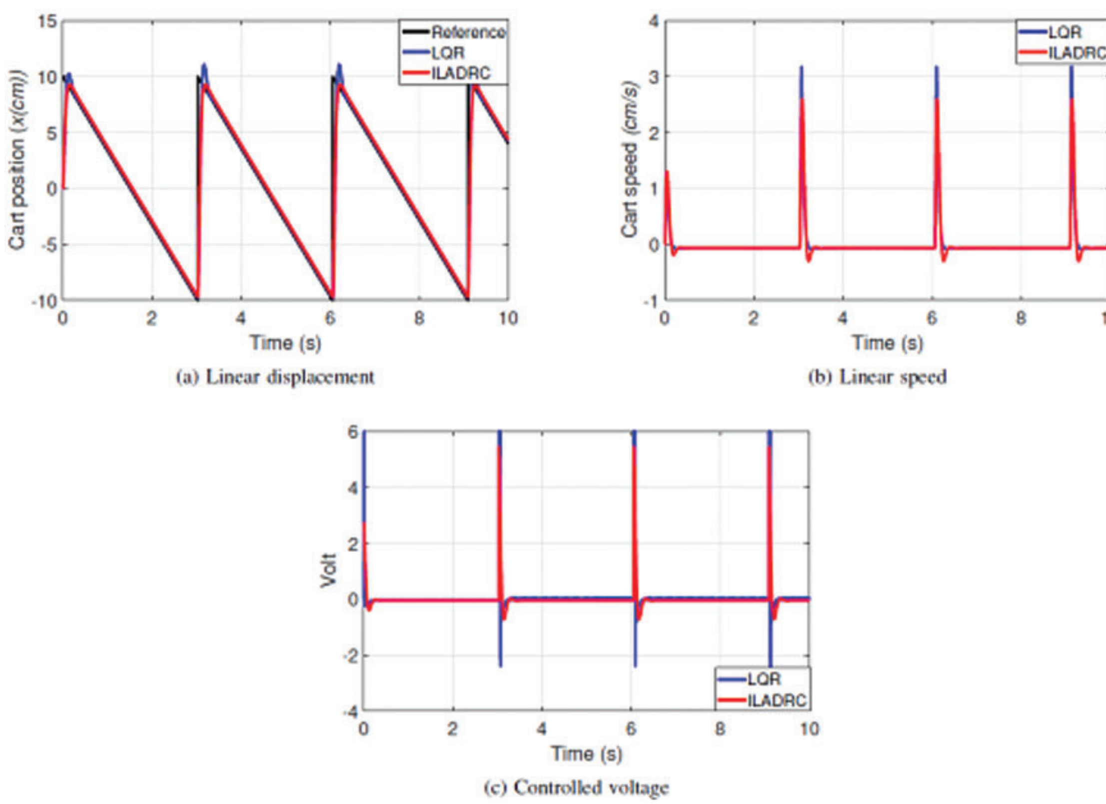


Figure 6: Results: Saw profile

7 Conclusion

Servo cart systems play a vital role in a number of automated systems because of their displacement and speed control. In this work, an ILADRC control technique is developed for displacement and speed control of linear servo carts. Several speed and position control technique-based related work was initially studied and analyzed. It is proposed to control a minimum phase-stable system using a LADRC structure with an integrated action (ILADRC). This contribution consists a novel design method is proposed for the ILADRC scheme based on the BITF. As elaborated in the previous section, a novel design method is proposed for the SPT controller. A critical contribution to the design of the LADRC control scheme is to use it from a practical point of view. Using results obtained from experiments on the linear servo cart system (LSC), the effectiveness of the proposed ILADRC scheme is illustrated. Results show improvements in robustness due to the rejection of disturbances in ILADRC scheme. In addition, results are compared between the integral-based LADRC and the traditional LQR schemes which are based on statistical methods.

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