A Gantry Crane Control Using ADRC and Input Shaping

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Abstract

Gantry cranes are wildly used in various fields such as industry and transportation. There are various approaches to control cranes, but most of them are difficult in design and implementation in practice. Input shaping technique in combination with traditional PID controller is a practical approach but its performance is easily degraded by disturbance and parameter uncertainty. This paper proposes ADRC in combination with Input shaping approach in which ADRC is used to reject disturbance while keeping the simplicity in design as PID controller, and Input shaping plays the role of vibration suppression. Simulations show the effectiveness of the proposed approach.

Keywords: ADRC, Extended Observer, Input Shaping.

1. Introduction

Cranes play an important role in various fields such as industry, transportation, construction, etc. They are increasingly used and becoming larger, faster, and necessitating efficient controllers to guarantee fast turn-over time to meet safety requirements. One of the most challenged problems in controlling of crane is the payload pendulation/oscillation suppression. Over the past decades, the anti-sway or oscillation suppression control has been extensively researched, from open-loop (such as input-shaping [1], hybrid shape control [2]), closed-loop control (linear control, optimal control, adaptive control, see [3] for details), to intelligent control (fuzzy control, neural network, genetic algorithm, see [4] for more details). But most of them are complicated and difficult to implement in practice, especially with closed-loop control and intelligent control. The open-loop control such as input shaping is quite simple and usually is combined with PID controller of crane cart to suppress the oscillation of payload. This can be applied in practice, however, it performance is easily degraded by disturbance and parameter uncertainty.

In recent years, Active Disturbance Rejection Control (ADRC) is interested in to replace the traditional PID controller. This concept was originally proposed by J. Han [5, 6], but only becomes transparent to application engineers since a new parameter tuning method is proposed in [7]. This control method shows several advantages for disturbance rejection and for process with inaccurate parameters. ADRC is a powerful control method where system models are expanded with a new state variable, including all unknown kinetic and disturbance, that commonly happens in system formulation. The new state is estimated by using the Extended State Observer (ESO). ADRC has been applied for controlling of various systems such as for rigid coupling motion control system [8], decoupling control for multivariable system [9], flexible system [10], three-axis didactic radar antenna control system [11]. ADRC approach is also used to control the payload's position of crane system [12]. In this paper, in order to further improve the performance of the system while keeping the simplicity in designing the controller for practical use, the combination of input shaping with ADRC is proposed. ADRC, the replacement of PID controller, can be simply designed, but can reject the effect of disturbances.

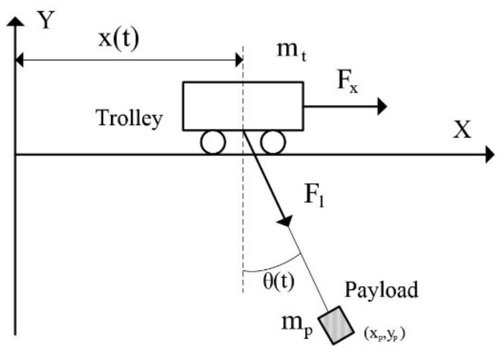

Fig. 1. An overhead crane system.

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2. Mathematical Model

The gantry crane system is illustrated in Fig. 1, where x is the horizontal position of trolley, l is the length of the hoisting cable and θ is the sway angle.

For the sake of simplicity, both the trolley and the payload are considered as point masses and the friction between the trolley and the rail is neglected. The equations for the gantry crance model are [13]:

$$\begin{aligned}&(m_1+m_2)\ddot{x}+m_2 l\ddot{\theta}\cos\theta+m_2\ddot{l}\sin\theta\\&+(2m_2\dot{l}\cos\theta-m_2 l\dot{\theta}\sin\theta)\dot{\theta}=F_X\end{aligned}\tag{1}$$

$$l\ddot{\theta}+2\dot{\theta}\dot{l}+\ddot{x}\cos\theta+g\sin\theta=0\tag{2}$$

$$m_2(\ddot{l}+\ddot{x}\sin\theta-l\dot{\theta}^2-g\cos\theta)=F_L\tag{3}$$

Suppose that the tension force that will cause the hoisting cable to elongate is neglected, thus l can be assumed to be constant and $\dot{l}=\ddot{l}=0$. We have then the equation (1), (2) and (3) become:

$$(m_t+m_p)\ddot{x}+m_p l\ddot{\theta}\cos\theta-m_p l\dot{\theta}^2\sin\theta=F_X\tag{4}$$

$$l\ddot{\theta}+\ddot{x}\cos\theta+g\sin\theta=0\tag{5}$$

$$m_2(\ddot{x}\sin\theta-l\dot{\theta}^2-g\cos\theta)=F_L\tag{6}$$

3. Control System Design

3.1 Position control of the trolley

3.1.1 ADRC Concept

The concept of ADRC was pioneered by J. Han [5]. A second order plant is considered:

$$\ddot{y}(t)=f\left(t,\dot{y},y,\omega\right)+b_0.u(t)\tag{7}$$

where u is the control input, y is the output and ω is the disturbance. According to Han, the generalized term $f\left(t,\dot{y},y,\omega\right)$ (from now on f is used to denote $f\left(t,\dot{y},y,\omega\right)$ where applicable) is insignificant while only its real time estimate $\hat{f}$ is important. Therefore, an Extended State Observer (ESO) is constructed to provide $\hat{f}$ such that we can compensate the impact of f on the model by means of disturbance rejection. This allows the control law to be constructed as:

$$u=\frac{u_0-\hat{f}}{b_0}\tag{8}$$

to reduces the plant in (7) to a form of:

$$\ddot{y}(t)\simeq u_0\tag{9}$$

which can be easily controlled. In general, this concept is applicable to higher order systems. It requires little knowledge of the plant, the only thing required is the knowledge of the order of the plant and the approximate value of parameter b_0. The convergence of linear ESO is extensively discussed in [14].

The ESO was originally proposed by J. Han [6] and made practical by the tuning method proposed by Gao [7], which simplified its implementation and made the design transparent to engineers. The main idea is to use an augmented state space model of equation (7) that includes f as an additional state. In particular, let $x_1=y$, $x_2=\dot{y}$ and $x_3=f$.

The augmented state space form of equation (7) is:

$$\begin{pmatrix}\dot{x}_1(t)\\\dot{x}_2(t)\\\dot{x}_3(t)\end{pmatrix}=\underbrace{\begin{pmatrix}0&1&0\\0&0&1\\0&0&0\end{pmatrix}}_{A}\begin{pmatrix}x_1(t)\\x_2(t)\\x_3(t)\end{pmatrix}+\underbrace{\begin{pmatrix}0\\b_0\\0\end{pmatrix}}_{B}.u(t)+\begin{pmatrix}0\\0\\1\end{pmatrix}\dot{f}(t)$$

$$y(t)=\underbrace{\begin{pmatrix}1&0&0\end{pmatrix}}_{C}\begin{pmatrix}x_1(t)\\x_2(t)\\x_3(t)\end{pmatrix}\tag{10}$$

The state observer can be formulated as:

$$\begin{aligned}\begin{pmatrix}\dot{\hat{x}}_1(t)\\\dot{\hat{x}}_2(t)\\\dot{\hat{x}}_3(t)\end{pmatrix}&=\begin{pmatrix}0&1&0\\0&0&1\\0&0&0\end{pmatrix}\begin{pmatrix}\hat{x}_1(t)\\\hat{x}_2(t)\\\hat{x}_3(t)\end{pmatrix}+\begin{pmatrix}0\\b_0\\0\end{pmatrix}.u(t)+\begin{pmatrix}l_1\\l_2\\l_3\end{pmatrix}\left(y(t)-\hat{x}_1(t)\right)\\&=\underbrace{\begin{pmatrix}-l_1&1&0\\-l_2&0&1\\-l_3&0&0\end{pmatrix}}_{A-LC}\begin{pmatrix}\hat{x}_1(t)\\\hat{x}_2(t)\\\hat{x}_3(t)\end{pmatrix}+\underbrace{\begin{pmatrix}0\\b_0\\0\end{pmatrix}}_{B}.u(t)+\begin{pmatrix}l_1\\l_2\\l_3\end{pmatrix}.y(t)\end{aligned}\tag{11}$$

where l_1, l_2 and l_3 are observer parameters to be determined such that $\hat{x}_1$, $\hat{x}_2$ and $\hat{x}_3$ will track y, $\dot{y}$ and f respectively.

Then the control law

$$u=\frac{u_0-\hat{x}_3}{b_0}\text{ with }u_0=K_P.(r-\hat{x}_1)-K_D.\hat{x}_2\tag{12}$$

reduces equation (7) to:

$$\ddot{y}(t)\simeq u_0=K_P(r(t)-y(t))-K_D.\dot{y}(t)\tag{13}$$

where r is the set point.

Taking the Laplace Transform of (13), one has the close-loop transfer function as follows:

$$G_{cl}(s)=\frac{Y(s)}{R(s)}\simeq\frac{K_P}{s^2+K_Ds+K_P}\tag{14}$$

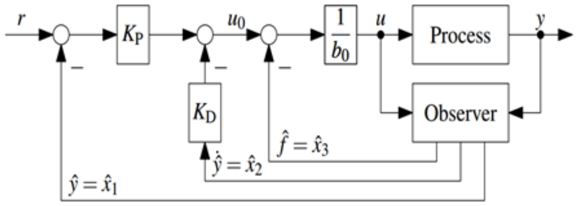

Fig. 2. ADRC for a second order plant.

3.1.2 ADRC for trolley's position control

To apply the ADRC presented in previous section, we rewrite equation (4) to be the same form as equation (7):

$$\begin{aligned}\ddot{x} &= \frac{m_p}{m_t+m_p}\left(l\dot{\theta}^2\sin\theta - l\ddot{\theta}\cos\theta\right) + \frac{1}{m_t+m_p}F_X \quad (15)\\ &= f(t) + b_0.u(t)\end{aligned}$$

where

$$f(t) = \frac{m_p}{m_t+m_p}\left(l\dot{\theta}^2\sin\theta - l\ddot{\theta}\cos\theta\right);$$

$$u(t) = F_X$$

According to [15], the ADRC's parameters can be as follows:

- Get the desired 2% settling time T_{settle}.
- Choose K_P and K_D to get a negative-real double pole, $s_{1/2}^{CL} = s^{CL}$:

$$K_p = \left(s^{CL}\right)^2,\ K_D = -2.s^{CL} \text{ with } s^{CL} = -\frac{6}{T_{settle}} \quad (16)$$

- Since the observer dynamics must be fast enough, the observer poles $s_{1/2}^{ESO}$ must be placed left of the close-loop pole s^{CL}, for suggestion:

$$s_{1/2}^{ESO} = s^{ESO} \approx (3...10).s^{CL} \quad (17)$$

- The observer parameters can be computed from its characteristic polynomial:

$$\begin{aligned}\det\left(sI - \left(A - LC\right)\right) &= s^3 + l_1 s^2 + l_2 s + l_3 \quad (18)\\ &\overset{!}{=} \left(s - s^{ESO}\right)^3\end{aligned}$$

Then

$$l_1 = -3.s^{ESO}, l_2 = 3.\left(s^{ESO}\right)^2, l_3 = \left(s^{ESO}\right)^3 \quad (19)$$

3.2 Input Shaping

3.2.1 Input Shaping concept

Input Shaping (IS)[1] is a feedforward technique for residual vibration suppression. A basic illustration of a input shaper which inlcudes two impulses (known as Zero Vibration shaper) is shown in Fig. 3.

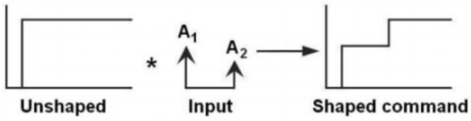

Fig. 3. Input Shaping Technique.

If an unshaped command is used to control the system and causes system's residual vibration, it is convoluted with pulse series to obtain shaped command that can suppress residual vibration.

In case the pulse series include two pulses with magnitude A_1 and A_2 at time instant t_1 and t_2 respectively, these parameters are determined as follows:

$$\begin{cases} A_1 = \dfrac{1}{1+K}, & t_1 = 0 \\ A_2 = \dfrac{K}{1+K}, & t_2 = \dfrac{\pi}{\omega_d} \end{cases} \quad (20)$$

where

$$K = \exp\left(-\frac{\pi\xi}{\sqrt{1-\xi^2}}\right), \quad (21)$$
$$\omega_d = \omega_n\sqrt{1-\xi^2}$$

ξ is the damping ratio and ω_n is the nature frequency of the system.

Two pulse series are sensitive to parameter variation, to improve the robustness of the input shaping, the Zero Vibration Derivative (ZVD) using three pulses series is designed with parameters [1]:

$$\begin{cases} A_1 = \dfrac{1}{1+2K+K^2}, & t_1 = 0 \\ A_2 = \dfrac{2K}{1+2K+K^2}, & t_2 = \dfrac{\pi}{\omega_d} \\ A_3 = \dfrac{K^2}{1+2K+K^2}, & t_3 = \dfrac{2\pi}{\omega_d} \end{cases} \quad (22)$$

where K and ω_d as the same as in (21).

3.2.2 ADRC with Input shaping

ADRC is used to control the trolley's position with disturbance rejection. However, the residual vibration of payload may still exist. Therefore, Input shaping is used in combination with ADRC to suppress the vibration. Assuming the sway angle is small, we have then: sinθ ≈ θ and cosθ ≈ 1. Equation (5) becomes

$$\ddot{x} + l\ddot{\theta} + g\theta = 0 \quad (23)$$

So, we will obtain:

$$\frac{\theta(s)}{X(s)} = \frac{-s^2}{ls^2 + g} \qquad (24)$$

The individual frequency of sway: $\omega_n = \sqrt{g/l}$

Factor of the damped oscillation: $\xi = 0$

So, to reduce the vibration excited by the trolley motion, the parameters of ZVD shaper are:

$$\begin{cases} A_1 = \dfrac{1}{1+2K+K^2} = 0.25, & t_1 = 0 \\ A_2 = \dfrac{2K}{1+2K+K^2} = 0.5, & t_2 = \dfrac{\pi}{\sqrt{g/l}} \\ A_2 = \dfrac{K^2}{1+2K+K^2} = 0.25, & t_2 = \dfrac{2\pi}{\sqrt{g/l}} \end{cases}$$

The structure of ADRC with Input shaping controller is shown in Figure 4. ADRC is used to control the trolley to track the desired input trajectory. The IS is used to reduce the vibration excited by the trolley motion.

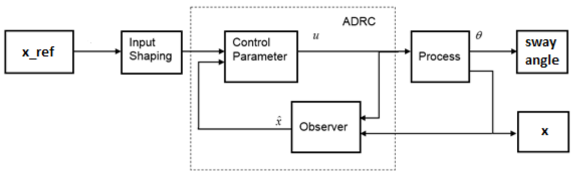

Fig. 4. ADRC with Input Shaping controller.

3.3 Simulation

To verify the effectiveness of the proposed control structure, simulations are done with the following parameters:

Table 1. The system's parameters [9]

Symbol	Description	Value
m_t	Mass of the trolley	0.536 (kg)
m_p	Mass of the load	0.375 (kg)
l	Rope length	0.64 (m)

The parameters for ADRC controller design is chosen as follows:

$b_0 = 1/(m_t + m_p) = 1.1$

$T_{settle} = 4\ [s]$

$s^{ESO} = 9.s^{CL}$

We will compare the performance of ADRC with PID-IS combined controller ($K_P = 5$, $K_I = 1$, $K_D = 4$ [9]) and ADRC-IS combined controller. In this comparison, a 2-1-2 trajectory type reference signal for the trolley placement is used.

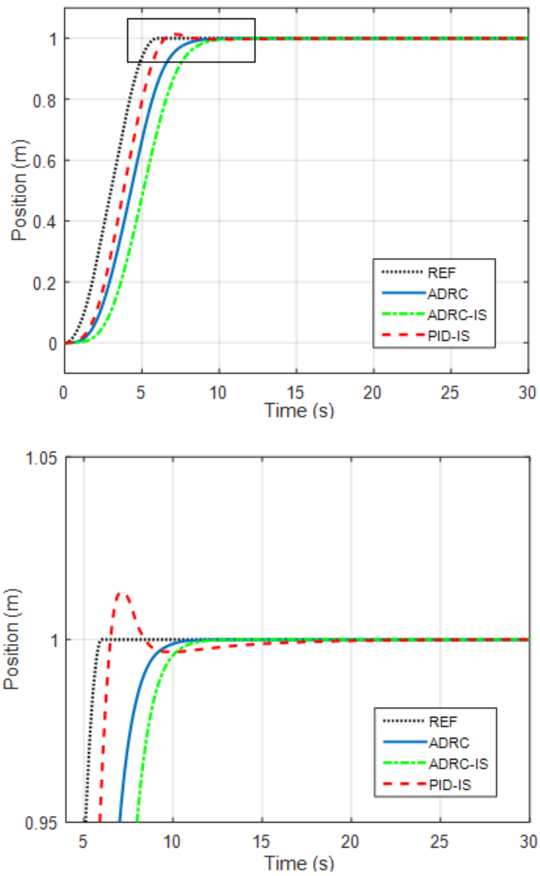

Fig. 5. Trolley displacement - no disturbance.

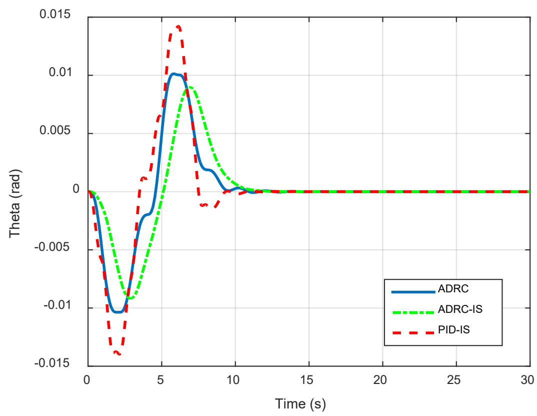

Fig. 6. Payload's sway angle - no disturbance.

In the first simulation, the system without disturbance is considered. The displacement of trolley and sway angle of the payload with three considered controllers are shown in Figure 5 and 6 respectively. It is observed that all the controllers have good performance. The ADRC and PID+IS are have the *similar quality. The ADRC+IS is slower, but the residual vibration is smallest among these controllers.*

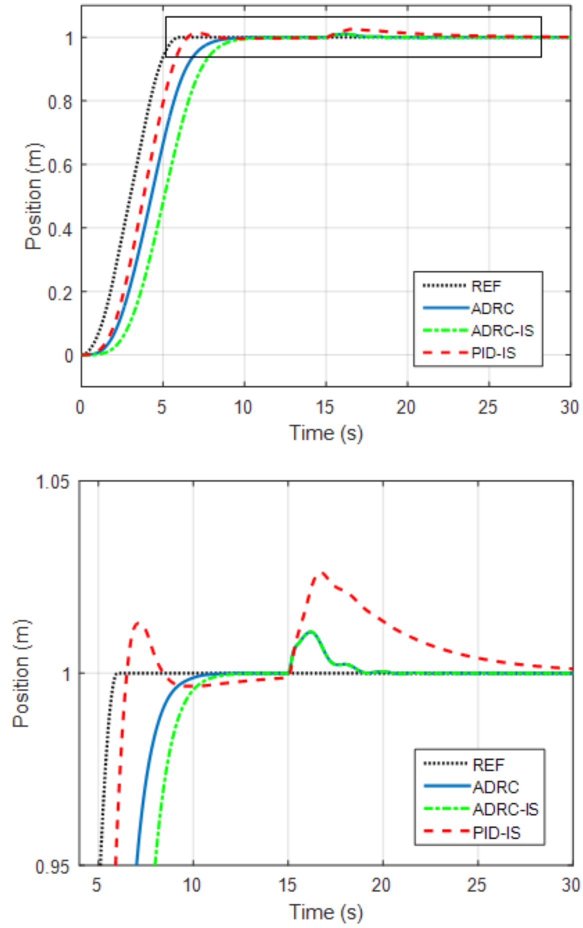

Fig. 7. Trolley's displacement - constant disturbance

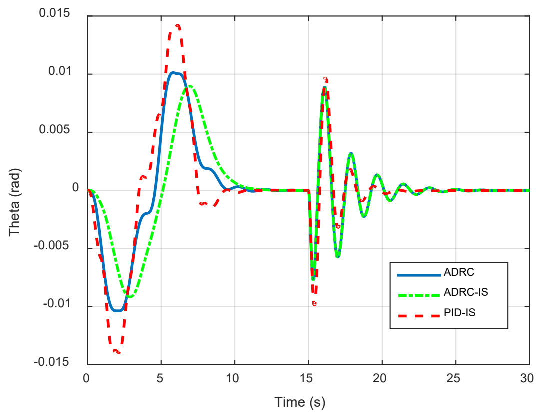

Fig. 8. Payload's sway angle - constant disturbance

In second simulation, in order to test the robustness of the ADRC approach, a disturbance 0.15(N) which acts on trolley are introduced in the simulation at t = 15s. The simulation results are shown in Fig. 7 for trolley's position and in Fig. 8 for payload sway angle.

It can be seen that the ADRC and ADRC+IS can settle the the trolley's position much faster than PID+IS. It means that the ADRC controller can reject the disturbance better than PID.

However, because the input shaping is feedforward controller that cannot effect to the system's disturbace, the residual vibration caused by disturbance cannot be reduced as seen in Figure 8. Another reason is that ADRC controller is designed to reject the disturbance for trolley only. There is a trade off between the payload's sway angle and settling time of trolley position. These problems will be considered carefully in the next researches.

4. Conclusion

The paper has proposed the ADRC in combination with Input shaping controller. Simulations show that this structure outperforms the ADRC and PID+IS structures both in disturbance rejection and vibration suppression. Besides, the simplicity in designing process promises its wide application in future.

In the next step, the practical implementation of this approach will be done. The problem of reducing residual vibration caused by disturbance will be considered. In addition, its application in other systems are also considered.

References

[1] Huey, John Rogers. The intelligent combination of input shaping and PID feedback control PhD diss., Georgia Institute of Technology, 2006.

[2] Yano, Kenichi, and Kazuhiko Terashima. Development and evaluation of operator support system for rotary cran. In Control Applications,(CCA) & Intelligent Control,(ISIC), 2009 IEEE, pp. 1637-1642. IEEE, 2009.

[3] Abdel-Rahman, Eihab M., Ali H. Nayfeh, and Ziyad N. Masoud. Dynamics and control of cranes: A review Modal Analysis 9, no. 7 (2003): 863-908.

[4] Hyla, Paweł. The crane control systems: A survey In Methods and Models in Automation and Robotics (MMAR), 2012 17th International Conference on, pp. 505-509. IEEE, 2012.

[5] J. Han, From PID to active disturbance rejection control, IEEE Trans. Ind. Electronics., (2009), Vol 56, No.3, pp. 900-906.

[6] Z. Gao, Y. Huang, J. Han, An alternative paradigm for control system design. Proceedings of 40th IEEE Conference on Decision and Control, Orlando, Florida, December 4-7, (2001), pp. 4578-4585.

[7] Z. Gao, Scaling and Parameterization Based Controller Tuning, Proceedings of the 2003 American Control Conference, (2003), pp. 4989–4996.

[8] Y. X. Su, C. H. Zheng, B. Y. Duan (2005), Automatic disturbances rejection controller for precise motion control of permanent-magnet synchronous motors, IEEE Trans. Ind. Electron. 52, 814–823.

[9] Q. Zheng, Z. Chen, Z. Gao (2007), A Dynamic Decoupling Control and Its Applications to Chemical Processes. Proceeding of American Control Conference, New York, USA.

[10] H. Yang et al. (2015), Back-stepping control of two-link flexible manipulator based on an extended state observer, Advance in Space Research, Vol.56, No.10, pp. 2312-2322.

[11] M. R. Stankovíc et al. (2016), FPGA system-level based design of multi-axis ADRC controller, Mechatronics, Vol 40, pp. 146-155.

[12] T. Cai, H. Zhang, L. Gu, Z. Gao, On active disturbance rejection control of the payload position for gantry cranes, 2013 American Control Conference, USA, (2013), pp.425-430.

[13] M. Maila, S. Y. China, Disturbance rejection control applied to a gantry crane, Jurnal Mekanikal, (2008) No.25, 64-79.

[14] D. Yoo, S. S. T. Yau, Z. Gao, On convergence of the linear extended observer, Proceedings of the IEEE International Symposium on Intelligent Control, Munich, Germany. (2006), pp. 1645–1650.

[15] G. Herbs, A Simulative Study on Active Disturbance Rejection Control as a Control Tool for Practitioners, In Siemens AG, Clemens-Winkler-Strabe 3, Germany (2013).