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Robotic excavator motion control using a nonlinear proportional-integral controller and cross-coupled pre-compensation

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ABSTRACT

For a robotic excavator, there is no operator in the cab while it is working, so the moving trajectory of the bucket teeth is planned in advance. For such a multi-joint machine, the coordinate motion control algorithm must be properly designed to achieve high tracking precision. However, due to uncertainty of the load and fluctuation of the speed, the multi-actuator system cannot work stably, resulting in tracking errors. To improve tracking performance, a cross-coupled pre-compensation algorithm is put forward in this paper. It is combined with nonlinear proportional-integral controllers to optimize the control parameters of the actuators. Experiments are performed on a 3.5-ton exactor. The results show that the proposed control algorithm is effective for improving the tracking accuracy.

1. Introduction

As excavators are often used to accomplish dangerous tasks, a robotic excavator, which can operate without an operator in the cab, can greatly improve safety. Kim [1] proposed a set of analytic gradient-based motion optimization algorithms to plan an optimized trajectory for an unmanned excavator. Tiwari [2] provided a way to classify the bucket trajectory; this approach could assist in the operation of excavators. For an excavator, the motion of each actuator is controlled by a separate closed-loop controller, such as neural adaptive control [3], robust adaptive control [4], and sliding mode control [5]. However, single actuator control cannot guarantee accuracy for an unmanned excavator. As a result, additional coordinated control of the multi-actuators must be conducted. Due to the inherent nonlinearity of the hydraulic system, the load uncertainty, and the structural differences, the four-axis system is not able to provide stable operation, resulting in errors. There are two types of errors: tracking error, which is the distance from the actual position to the expected position, and contour error, which is the smallest deviation from the expected contour to the actual position. There are few reports regarding multi-actuator coordinated control in hydraulic excavators. Some studies related to contour control are reported in other applications [6,7]. Yang [8] proposed a contour error estimation method for contour following applications; the method was found to improve the tracking performances greatly. Zhang [9] presented an analytical prediction and compensation for contouring errors in five-axis machining of splined tool paths. Cheng [10] attempted to reduce contour error for free-form contour following tasks of biaxial motion control systems by using a fuzzy logic-based feed rate regulator. The concept of cross-coupled control of multi-axis was also proposed in refs. [11–13]. It has been reported that the cross-coupled controller has a better contouring accuracy than the uncoupled one.

In this paper, the cross-coupled pre-compensation (CCP) is applied in a hydraulic robotic excavator. It is combined with the nonlinear proportional–integral (PI) controllers of each actuator to accomplish coordinated control of the unmanned excavator. The remainder of this paper is divided into five sections: Section 1 presents an overview of the nonlinear PI controller for a single actuator. The introduction of CCP algorithm is given in Section 2. Section 3 provides details on the application of the proposed algorithm. Section 4 shows experimental validation of CCP and nonlinear PI controller. This section also discusses additional considerations, which are required to apply the algorithms. And the experimental results are also given in the section. Finally, Section 5 presents conclusions and future directions for this work.

2. Nonlinear PI controller for a single actuator

The nonlinear PI controller has the same functional form as the normal PI and is expressed by Eq. (1):

$$u = K_P e + K_I I \tag{1}$$

where $u$is the control value,$e$is the error of the target value,$K_P$is the proportional factor,$K_I$is the integral factor, and $I$is the integral value.

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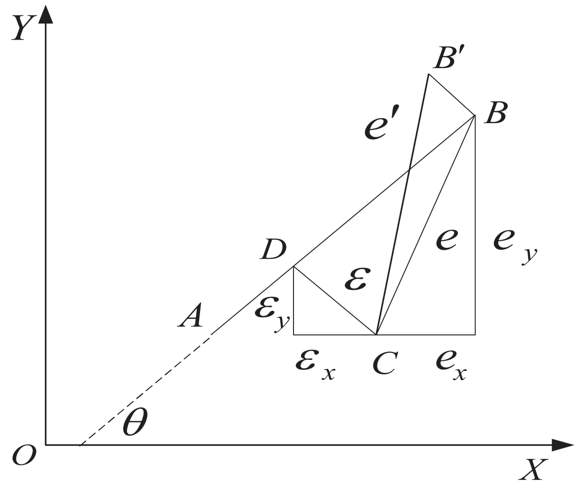

Fig. 1. Definition of the variables in the cross-coupled algorithm.

However, for the nonlinear PI, $I$is different from the normal PI because it changes with the sampling time. The integral value can be expressed as Eq. (2)

$$I_t = (I_{t-\Delta T} + e\Delta T + K_a \ddot{q}_{in} \Delta T)\frac{a}{a+\dot{e}^2} \tag{2}$$

where t is the sampling time, ΔT is the sampling interval, I_t is the integral factor of the current sampling, $I_{t-\Delta T}$ is the integral factor of the last sampling, K_a is the integral factor of the angular acceleration, $\ddot{q}_{in}$ is the target angular acceleration, $\dot{e}$ is the difference change rate, and $a$is the compare factor.

If $\dot{e} = 0$, then $\frac{a}{a+\dot{e}^2} = 0$; if $\dot{e} \neq 0$, then $\frac{a}{a+\dot{e}^2} < 1$; and if $|\dot{e}| \to \infty$, then $\frac{a}{a+\dot{e}^2} \to 0$. Here, the value of a determines the convergence rate.

$\ddot{q}_{in}$ reduces the lag or overshoot when the actuator starts, stops, or changes direction. In addition, $\ddot{q}_{in}$ could continuously change$u$ when the target value changes. This approach could help avoid short pulse excitation and maintain stability.

3. CCP algorithm introduction

It is known that the bucket trajectory is composed of many discrete points and that the operations, such as digging and ground leveling, always occur in the vertical plane. Thus, the trajectory can be considered to approximately consist of many short straight lines in the same plane. Taking a linear path in Cartesian coordinates as an example, Fig. 1 shows the definition of the variables in this algorithm and their relationships.

In Fig. 1, AB is a planned straight path in the bucket tip trajectory, A is the current expected set-point, B is the next expected point, and C is the current actual position of bucket tip.θ is the angle between AB and X-axis, e is the tracking error, ande_x and e_y are the tracking error components along the X- and Y-axis, respectively.ε is the contour error. Similarly, $\varepsilon_x$andε_y are the contour errors in the X- and Y-axis, respectively. From Fig. 1, it can be found that

$$\varepsilon_x = e_x \sin^2\theta - e_y \sin\theta \cos\theta \tag{3}$$

$$\varepsilon_y = e_x \sin\theta \cos\theta - e_y \cos^2\theta \tag{4}$$

To reduce the contour error, the planned path should be pre-compensated. Thus, the next expected point B is compensated to pointB', the coordinate of which is $(x_B - K_C\varepsilon_x, y_B + K_C\varepsilon_y)$, where K_C is the gain coefficient. In this way, the next actual position of the bucket tip could be much closer to the expected point B, thereby improving tracking and regulating accuracies.

4. Application of the nonlinear PI controller with CCP in a robotic excavator

In a robotic excavator, because of the complexity of the structure, several methods are used to describe a joint position. The compensation for the bucket tip contour error is specified in a world coordinate system, but the control signal of each actuator is specified in the spatial coordinate system. As a result, to implement the CCP, coordinate transformation is required.

Fig. 2 depicts the D–H coordinates of the excavator. For a 3.5-ton excavator, the D–H coordinate parameters are shown in Table 1.

q_0–$q_3$are the angles of each actuator; x, y, and z are the coordinates in the x-, y-, and z-axis, respectively; and ζ is the bucket angle. If the angle $q(t) = (q_0(t), q_1(t), q_2(t), q_3(t))^T$ is measured, then according to the robotic structure, the bucket tip coordinates $\{x, y, z, \zeta\}^T$ can be calculated by using Eq. (5):

$$\left\{\begin{array}{l} x = \cos(q_0)[a_3 * \cos(q_1+q_2+q_3) + a_2 * \cos(q_1+q_2) + a_1 * \cos(q_1)] \\ y = \sin(q_0)[a_3 * \cos(q_1+q_2+q_3) + a_2 * \cos(q_1+q_2) + a_1 * \cos(q_1)] \\ z = a_3 * \sin(q_1+q_2+q_3) + a_2 * \sin(q_1+q_2) + a_1 * \sin(q_1) \\ \zeta = q_1+q_2+q_3 \end{array}\right\} \tag{5}$$

By reverse processing, if $\{x, y, z, \zeta\}^T$ is given, then $q(t) = (q_0(t), q_1(t), q_2(t), q_3(t))^T$can also be calculated.

Usually, when an excavator is digging, the cab does not swing ($q_0 \equiv 0$ and $y \equiv 0$). The CCP control only calculates the compensation for the

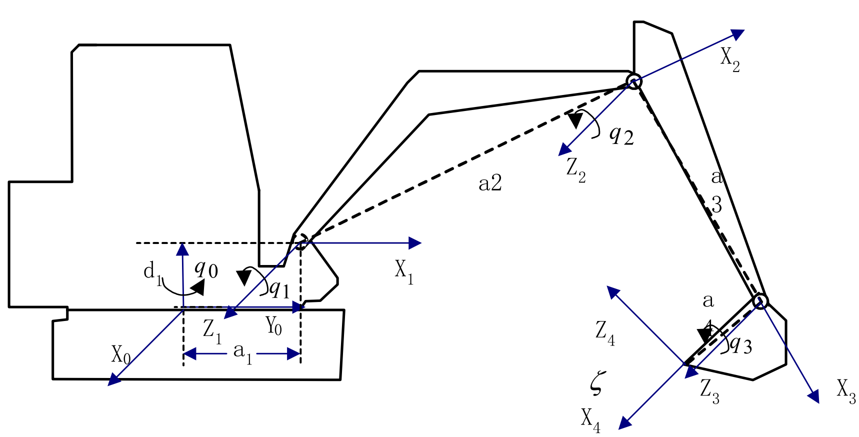

Fig. 2. D-H coordinates of the robotic excavator.