Design of a Database-Driven Control System for a Web Conveyor

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Abstract

Web Conveyor used in the processing of plastic films and other materials is a large-scale system consisting of multiple drive rolls, and it is difficult to understand the system characteristics during driving. This paper proposes a database-driven control scheme based on the FRIT scheme to implement motor control of this conveyor without system identification. To reduce the computational cost, the concept of database design based on similarity is introduced. The web conveyor's operating output can quickly achieve a reference signal, because it can be based on a database that holds operational data.

Keywords: PID Controller, Database-Driven Control, Web Conveyor

1. Introduction

A web is a thin, long material such as paper or plastic. It is used in a variety of applications, including paper rolls and wrapping film. Generally, the web is finally shipped as a rolled product. As a specific processing procedure, the web is stretched, printed, and rolled into a rolled product by a web conveyor. Ideally, the web feeding speed and tension should be kept constant during processing to prevent wrinkling and breakage. These are achieved by appropriately controlling the rotation of the multiple drive rolls in the web conveyor.

On the other hand, web characteristics change with temperature and humidity. Furthermore, the web conveyor characteristics are not constant according to the radius and moment of inertia of the drive rolls, which change during take-up. In addition, actual equipment includes uncertain dynamics such as bearing friction. For these reasons, it is difficult to determine appropriate control parameters for schemes that require knowledge of system characteristics.

Web conveyors are large-scale systems that contain many drive rolls. The application of decentralized control is being considered to improve its maintainability [1]. Furthermore, self-tuning of the web tension control system using the FRIT scheme has been proposed to solve the problem of difficulty in determining system characteristics [2]. However, this takes time to reach the reference signal because it requires parameter calculations for each operation.

Therefore, this paper applies database-driven control[3] to improve the control performance of web conveyors. Also, offline adjustment of control parameters using the same scheme is discussed. The database-driven control scheme can store past operational data. Therefore, it is possible to adjust control parameters offline based on the operational data. It is expected that the startup time of the next web conveyor will be reduced.

2. Overview of Web Tension Control System

2.1. *Modeling of a Web Tension Control System*

A schematic diagram of the web conveyor is shown in Fig. 1. The system consists of four drive rolls equipped with servomotors, two of which are equipped with sensors to measure tension. The web is transported from the unwinder, through the lead section and draw rolls to the winder.

In reference [1], the web has viscoelastic properties. Therefore, introduce the Voigt model of equation (1), which considers viscoelasticity as a characteristic of the web:

$$\boldsymbol{P}(\boldsymbol{s}) = \boldsymbol{A}\left(\boldsymbol{\eta_v} + \frac{\boldsymbol{G_v}}{\boldsymbol{s}}\right), \tag{1}$$

where G_v and η_v are the elastic modulus and viscous modulus, respectively.

The control variables in this paper are tension T_1 and T_3 and transfer speed V_2 and V_3.

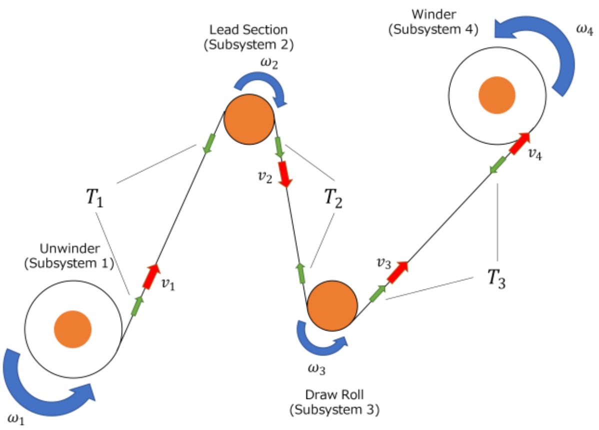

Fig. 1 Schematic diagram of web conveyor.

2.2. *Control System Design*

Fig. 2 shows a block diagram of the web conveyor control system. Subsystems 1 through 4 are assigned to each servo motor. In this paper, the "Controller Section" controls the four servo motors. In addition, a "Sequencer" is added to implement control to reduce instability caused by changes in the characteristics of the controlled object and mutual interference between the subsystems. "Sequencer" uses a proportional-priority PI controller (I-P controller) and applies a database-driven control scheme. The sampling time of the controller is set to 100 [ms] to avoid the upper limit of the computational cost by the PLC, assuming the verification in an actual experiment. In the "Controller section", a PI controller is used. Since the PI gain does not change, the sampling time of the controller is set to 10 [ms].

3. Database-Driven Control Scheme

3.1. *Database-Driven Control Schemes Based on Similarity*

When applying the database, as shown in Reference [4], the PI gains are determined by selecting a certain number of neighbors from the created database in the order of system conditions. Therefore, if the system conditions at the time of application differ significantly from those in the database, it may not be possible to determine the appropriate PI gain, because inappropriate neighbors may be selected. In addition, this controlled system is assumed to operate for a long period of time, up to one hour. Therefore, if the off-line adjustment of control parameters is performed based on the FRIT scheme, the number of databases becomes enormous. Correspondingly, the computational cost of off-line adjustment and determination of PI gains becomes very high. Depending on the calculation cost, the PLC may not be able to complete the calculation within the control cycle.

To address these problems, a database-driven control scheme based on similarity using kernel density estimation has been proposed [5]. The scheme can efficiently create databases because it calculates the similarity between a query and a database. It is also possible to select neighbors in the same way.

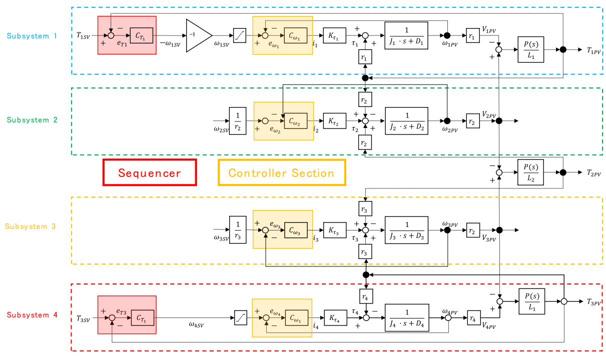

Fig. 2 Block Diagram of Web Tension Control System.

3.2. *Dataset*

The data sets required for the application of the database-driven control scheme are shown in equations (2) through (4) as follows:

$$\boldsymbol{\Phi_j} = [\bar{\boldsymbol{\phi}}(\boldsymbol{k_j}), \boldsymbol{\theta}(\boldsymbol{k_j})], \tag{2}$$

$$\begin{aligned}\bar{\boldsymbol{\phi}}(k_j) = [&r_0(k_j+1), r_0(k_j), y_0(k_j), \dots, y_0(k_j-n_y),\\ &\boldsymbol{u_0}(\boldsymbol{k_j}), \dots, \boldsymbol{u_0}(\boldsymbol{k_j}-\boldsymbol{n_u}),\\ &y_m(k_j), \dots, y_m(k_j-n_y)],\end{aligned} \tag{3}$$

$$\boldsymbol{\theta}(\boldsymbol{k_j}) = [\boldsymbol{K_P}(\boldsymbol{k_j}), \boldsymbol{K_I}(\boldsymbol{k_j})], \tag{4}$$

where j is the jth dataset in the database. Note that $r_0(t), u_0(t), y_0(t), y_m(t)$ are the operation data with the fixed PI gains, which are the reference signal, input, output, and reference output, respectively.

3.3. *Similarity Calculation*

When creating, training, or adapting a database, it is necessary to calculate the similarity between a query and a database for each case.
When adding new data $\bar{\boldsymbol{\phi}}(n)$, the similarity is calculated by the kernel density function-based similarity $S\left(\bar{\boldsymbol{\phi}}(n), \bar{\boldsymbol{\phi}}_A(k_j)\right)$ as follows:

$$\boldsymbol{S}\left(\bar{\boldsymbol{\phi}}(\boldsymbol{n}), \bar{\boldsymbol{\phi}}_{\boldsymbol{A}}(\boldsymbol{k_j})\right) = \prod_{i=1}^{n_y+n_u+1} \frac{1}{\sqrt{2\pi}\boldsymbol{h_i}} \boldsymbol{exp}\left(-\frac{\bar{\boldsymbol{\phi}}(\boldsymbol{n},\boldsymbol{i}) - \left(\bar{\boldsymbol{\phi}}_{\boldsymbol{A}}(\boldsymbol{k_j},\boldsymbol{i})\right)^2}{2\boldsymbol{h}_i^2}\right). \tag{5}$$

$\bar{\boldsymbol{\phi}}_A(k_j)$ is composed of the reference signal, input, and output, which are extracted from the dataset in equation (3) as follows:

$$\begin{aligned}\bar{\boldsymbol{\phi}}_A(k) = [&r_0(k_j+1), r_0(k_j), y_0(k_j), \dots, y_0(k_j-n_y),\\ &\boldsymbol{u_0}(\boldsymbol{k_j}), \dots, \boldsymbol{u_0}(\boldsymbol{k_j}-\boldsymbol{n_u})].\end{aligned} \tag{6}$$

Note that $\bar{\boldsymbol{\phi}}_A(k_j)$ in equation (6) refers to the k_{th} information vector and j element in the dataset $\bar{\boldsymbol{\phi}}_A$, and $\bar{\boldsymbol{\phi}}(n_j)$.
The h_i in equation (5) is the bandwidth and it is computed using the plug-in scheme similar to the one shown in reference [5]. The h_j is computed using the standard deviation σ_i and the mean μ_j when the number of data is N.

$$\boldsymbol{h_i} = \frac{\boldsymbol{1.06\sigma_i}}{\boldsymbol{N^{(1/5)}}} \tag{7}$$

$$\boldsymbol{\sigma_i} = \sqrt{\frac{\boldsymbol{1}}{\boldsymbol{N}}\left(\bar{\boldsymbol{\phi}}_{\boldsymbol{A}}(\boldsymbol{k_j},\boldsymbol{i}) - \boldsymbol{\mu_i}\right)} \tag{8}$$

$$\boldsymbol{\mu_i} = \frac{\boldsymbol{1}}{\boldsymbol{N}}\bar{\boldsymbol{\phi}}_{\boldsymbol{A}}(\boldsymbol{i}). \tag{9}$$

In equation (5), the highest similarity is obtained when the information vectors are exactly the same, as follows:

$$\boldsymbol{S}\left(\bar{\boldsymbol{\phi}}(\boldsymbol{n}), \bar{\boldsymbol{\phi}}(\boldsymbol{n})\right) = \prod_{i=1}^{n_y+n_u+1} \frac{1}{\sqrt{2\pi}\boldsymbol{h_i}}. \tag{10}$$

On the other hand, if the similarity is low, $S\left(\bar{\boldsymbol{\phi}}(n), \bar{\boldsymbol{\phi}}_A(k_j)\right) \to 0$. Here, a threshold $\alpha_{th}(0 < \alpha_{th} \leq 1)$ is introduced. Add new data only if the following equation (11) is satisfied for all data in the existing database:

$$\boldsymbol{S}\left(\bar{\boldsymbol{\phi}}(\boldsymbol{n}), \bar{\boldsymbol{\phi}}_{\boldsymbol{A}}(\boldsymbol{k_j})\right) < \boldsymbol{\alpha_{th}} \cdot \prod_{i=1}^{n_y+n_u+1} \frac{1}{\sqrt{2\pi}\boldsymbol{h_i}}. \tag{11}$$

In the same way, consider the case of determining the nearest neighbors. When applying the database, it is necessary to prevent the phenomenon that the number of neighbors tends to become zero when the output improves and differs significantly from the initial output. For this reason, the similarity is calculated from $\bar{\boldsymbol{\phi}}_A(k_j)$, in which the reference signal, output, and reference output are extracted from the data set in equation (8):

$$\begin{aligned}\bar{\boldsymbol{\phi}}_B(k_j) = [&r_0(k_j+1), r_0(k_j), y_0(k_j), \dots, y_0(k_j-n_y),\\ &\boldsymbol{y_m}(\boldsymbol{k_j}), \dots, \boldsymbol{y_m}(\boldsymbol{k_j}-\boldsymbol{n_y})].\end{aligned} \tag{12}$$

The nearest neighbors to the query $\bar{\boldsymbol{\phi}}_i(t)$ at some time t is assumed to satisfy the following equation (13) determined by the threshold $\beta_{th}(0 < \beta_{th} \leq 1)$:

$$\boldsymbol{S}\left(\bar{\boldsymbol{\phi}}_{\boldsymbol{i}}(\boldsymbol{t}), \bar{\boldsymbol{\phi}}_{\boldsymbol{B}}(\boldsymbol{k_j})\right) \geq \boldsymbol{\beta_{th}} \cdot \prod_{i=1}^{n_y+n_y+1} \frac{1}{\sqrt{2\pi}\boldsymbol{h_i}}. \tag{13}$$

4. Numerical Example Verification

4.1. *The threshold for similarity calculation*

The threshold value for initial database creation is $\alpha_{th} = 0.7$, and the threshold value for PI gain training and neighbors determination is $\beta_{th} = 0.1$.

4.2. *Simulation result and discussion*

First, simulations with fixed PI gains were performed to create the data set. The number of data acquired at that time was 1997, which was reduced to 234 and stored in the database. Next, the database was trained and simulations were performed using it. The results are shown in Fig. 3 and Fig. 4, which shows the results for subsystem 1.

Focus on the output result of the tension T_{1PV} in Fig. 3. It takes a very long time for the output to reach the reference signal, when controlled with the fixed PI gains. On the other hand, the control parameters are adjusted to correspond to the system characteristics, when database-driven control is applied. Therefore, it can be confirmed that the rise time is shorter compared to the control with the fixed PI gains.

Fig. 4 shows the results of PI gain transition and the number of neighbors in the sequencer section of subsystem 1. The PI gain fluctuates for about 10 seconds after the start of the simulation to improve the rise time.

The above results confirm that simulation with a database that has been trained improves the startup. In addition, efficient database creation was achieved by incorporating the concept of database-driven control based on similarity. Thus, the effectiveness of the database-driven control scheme for web conveyors was confirmed.

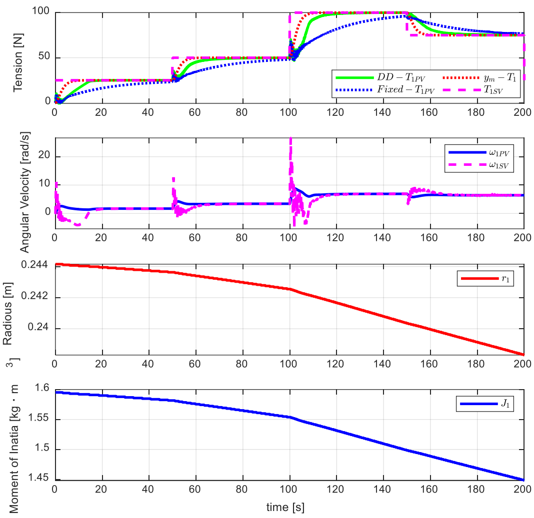

Fig. 4 Control result in subsystem 1 by the proposed scheme.

5. Summary

This paper proposed an offline adjustment scheme of PI gains by applying database-driven control to a web

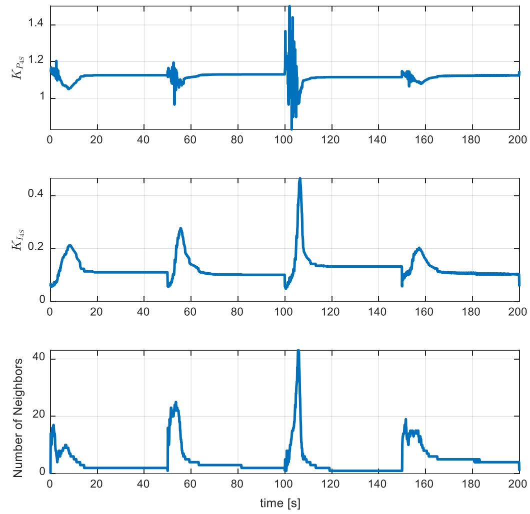

Fig. 3 The trajectories of PI gains and number of neighbors corresponding to Fig. 3.

tension control system. The effectiveness of the proposed scheme was verified using numerical examples.

Plans include the design of a reference signal filter, investigation of soft sensors, and experiments on actual equipment to further improve control performance.

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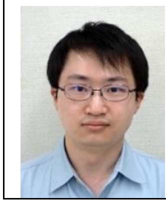

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