Neural Network Based Adaptive Control of Web Transport Systems

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***Abstract*— A tension control problem of a roll-to-roll web handling system is considered in the paper. It is shown that the dynamical response of the web handing system heavily depends on roll inertia. Dissimilar to other researches that based on the assumption of rolls with perfect cylindrical form and the web material having homogenous thickness, the paper takes imperfect roll-shape and nonhomogeneous web material into account. The two factors directly affect roll inertias during operating process. The novel contribution of the paper is a presentation of a neural network to estimate inertia momentums of unwinding and rewinding rolls that vary according to web material movement. The neural network is designed based on RBF network, estimating uncertainty of the roll inertia. The information on estimated inertia fed into a backstepping-sliding mode controller that ensure tension and velocity tracking of the system. The control design is presented in a systematical approach in the paper. The closed loop system stability is proven mathematically. The tracking performance is shown through several simulation scenarios.**

Keywords: roll-to-roll web system, backstepping, sliding mode controller, radial basis function (RBF).

I. INTRODUCTION

In today's world, numerous practical applications associated with web handling systems such as flexible displays, color-shifting, lighting, solar cells and so on utilizing roll-to-roll (R2R) systems are becoming extremely prevalent to handling industry. In order to restrict disturbance in the whole process, the control algorithms for R2R systems are indispensable [1] for high printing resolution. First, basing on dynamic modelling of system illustrated by some researchers [2], Xu et.al [3], several papers have been published to enhance speed and tension control with various control algorithm such as sliding mode control (SMC) [4], back-stepping control [5] to counter effects of disturbances for non-linear span R2R systems. Apart from that, the consideration of rotational roll inertia which affect directly the speed and quality of systems was also taken into account by several authors [6] and [7]. By implement of observer-based feedback control [8] and [9], the controller proposed by Lin el.al posses good disturbance caused by friction and rotational roll inertia rejection property. However, when parameters of the system accompanied by external varying disturbance, those controllers in the aforementioned articles can hardly guarantee efficiency and quality control in production. Hence, it is strictly essential to develop a adaptive controller with good stability for control of the R2R systems. With the rapid growth of digital computers a neural network has become a powerful tool [10] addressing complex requirements of the system that other techniques could hardly solve. The power of this approach is demonstrated by utilizing a prediction model to deal with all of the negative effects of systems. Additionally, the weights of layers are updated constantly to ensure the Lyapunov stability. By taking the advantage of Backstepping and sliding mode control(BSMC), this paper proposes a new approach control which used SMC Backstepping integrated with RBF neural network(RBFN-BSMC) to builds the adaptive system of roll- to-roll at steady-state operating condition.

II. BACKSTEPPING SLIDING MODE CONTROLLER FOR ROLL TO ROLL WEB SYSTEM.

A. *Roll-to-roll web system modelling*

The single-span roll-to-roll web control system is shown in Figure 1 contains unwinder, rewinder and a loadcell subsystem with idle rollers. The torques τ_u , τ_r generated on unwinder, rewinder motors control web's velocity and tension.

Assuming that web slippage and deformation are totally ignored, the loadcell dynamic and friction are not taken into account, and web property obeys Hook's law. The non-linear dynamic equations of single-span roll-to-roll web control system are shown as[3]:

$$\dot{\omega}_u = c_1\omega_u + c_2 T + c_3\tau_u, \quad (1)$$

$$\dot{T} = c_4\omega_u + c_5 T\omega_r + c_6\omega_r, \quad (2)$$

$$\dot{\omega}_r = c_7 T + c_8\omega_r + c_9\tau_r. \quad (3)$$

Where:

$$c_1 = \frac{B_u}{J_u}, \quad c_2 = \frac{R_u}{J_u}, \quad c_3 = -\frac{1}{J_u}, \quad c_4 = -KR_u,$$

$$c_5 = -\frac{Rr}{L}, \quad c_6 = KR_r, \quad c_7 = \frac{R_r}{J_r}, \quad c_8 = -\frac{B_r}{J_r},$$

$$c_9 = \frac{1}{J_r}.$$

The relevance among total moment of inertia, operating radius and the thickness of web is shown in following equations:

$$R_u(t) = R_{u0} - \frac{\theta_u h}{2\pi} \quad (4)$$

$$R_r(t) = R_{r0} + \frac{\theta_r h}{2\pi} \quad (5)$$

$$J_u = J_{u0} + \pi\rho\varpi\frac{\left(R_u^4 - R_{u0}^4\right)}{2} \quad (6)$$

$$J_r = J_{r0} + \pi\rho\varpi\frac{\left(R_r^4 - R_{r0}^4\right)}{2} \quad (7)$$

Where:

T : web tension

J_u : moment of inertia of the unwind roll and motor

J_r : moment of inertia of the rewind roll and motor

R_u : radius of the unwind roll

R_r : radius of the rewind roll

B_u : Coefficient of vicious friction of the unwind roll

B_r : Coefficient of vicious friction of the unwind roll

K : spring constant of web

L : total length of web

h : the thickness of web

ρ : the density of web

ϖ : the width of web

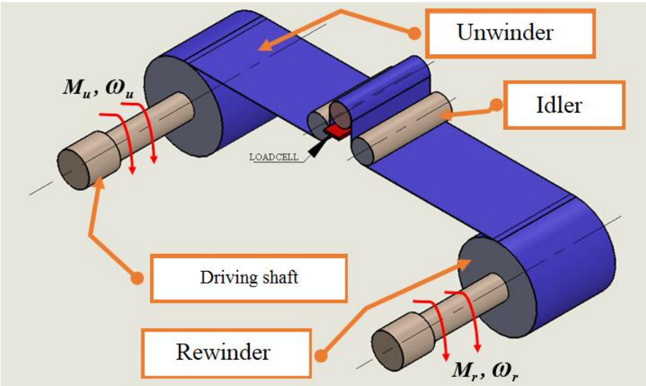

Fig. 1: Single-span web control system

B. *Backstepping sliding mode control*

The controller's purpose is keeping web tension and web speed at desired values, web speed is controlled through tracking angular velocity at references. This section uses sliding algorithm based on backstepping technique to design controller. The following design steps:

Step 1: Defining tracking error variables belows:

$$\bar{T} = T - T_d, \quad (8)$$

$$\bar{\omega}_u = \omega_u - \omega_{ud}, \quad (9)$$

$$\bar{\omega}_r = \omega_r - \omega_{rd}. \quad (10)$$

Where T_d, ω_{rd} are desired web tension and desired rewind angular velocity of web, respectively. And ω_{ud} is a unknown function that will be designed so that T tends to T_d.

Step 2: Determining control signal ω_{ud} such that web tension tracks the desired value. Rewritting equation (2) as:

$$\dot{\bar{T}} = c_4\omega_u + c_5 T\omega_r + c_6\omega_r \quad (11)$$

To regulate the error $\bar{T} \to 0$, choosing ω_{ud} as:

$$\omega_{ud} = -\frac{1}{c_4}\left(c_5 T\omega_r + c_6\omega_r + k_1\bar{T}\right) \quad (12)$$

Where k_1 is a positive gain. Proposing Lyapunov candidate function as:

$$V_T = \frac{1}{2}\bar{T}^2 \quad (13)$$

Using (11) and taking time derivative of (13) we obtain:

$$\dot{V}_T = \bar{T}\left(c_4\omega_u + c_5 T\omega_r + c_6\omega_r\right) \quad (14)$$

Next, replacing ω_u by ω_{ud} that is determinded in (12) results in:

$$\dot{V}_T = -k_1\bar{T}^2 \le 0$$

Step 3: Base on backstepping technique, we will determind control signal τ_u, τ_r in order to ω_u track ω_{ud} and ω_r track ω_{rd}. From (1), (3) and (9), (10) we obtain error equations:

$$\dot{\bar{\omega}}_u = c_1\omega_u + c_2 T + c_3\tau_u - \dot{\omega}_{ud} \quad (15)$$

$$\dot{\bar{\omega}}_r = c_8\omega_r + c_7 T + c_9\tau_r - \dot{\omega}_{rd} \quad (16)$$

Define sliding surfaces bellows:

$$S_u = \bar{\omega}_u \quad (17)$$

$$S_r = \bar{\omega}_r \quad (18)$$

Proposing Lyapunov candidate function as:

$$V_u = \frac{1}{2}S_u^{\ 2} \quad (19)$$

Differentiating (19) gives:

$$\dot{V}_u = S_u\dot{S}_u \quad (20)$$

The control signal is calculated as:

$$\tau_u = \tau_{ueq} + \tau_{usw} \quad (21)$$

Where τ_{ueq} is control component making $\dot{S}_u = 0$, τ_{usw} is control component so that $\dot{S}_u \le 0$. From (15), that is easy to get τ_{ueq} as:

$$\tau_{ueq} = -\frac{1}{c_3}\left(c_1\omega_u + c_2 T - \dot{\omega}_{ur}\right) \quad (22)$$

In order to guarantee $\dot{S}_u \le 0$, we proposing signal τ_{usw} as:

$$\tau_{usw} = -\frac{k_2}{c_3}sat\left(S_u\right) \quad (23)$$

Where k_2 is a positive gain. From (15), (17), (20), (21), (22) and (23), we obtain:

$$\dot{V}_u = -k_2 S_u sat\left(S_u\right) \le 0$$

Similarly, the control signal τ_r is generated by taking the total τ_{req} and τ_{rsw}, where:

$$\tau_{req} = -\frac{1}{c_9}\left(c_8\omega_r + c_7 T - \dot{\omega}_{rr}\right) \quad (24)$$

$$\tau_{rsw} = -\frac{k_3}{c_9}sat\left(S_r\right) \quad (25)$$

Where k_3 is a positive gains.

III. ADAPTIVE BACKSTEPPING-SLIDING MODE CONTROLLER FOR UNCERTAINTIES OF ROLL TO ROLL WEB SYSTEM

In practice, moment of inertia of unwind and rewind roll are uncertain, hence, some system parameters are unknown: $J_u, J_r, c_1, c_2, c_3, c_7, c_8$, and c_9. This section proposes a mechanism to estimate these parameters based on RBF network. The input of the neural network are ω_u, ω_r and the output are $\hat{J}_u, \hat{J}_r$ that are estimated values. Neural network is trained online in order to force error between actual and estimated values approach zero.

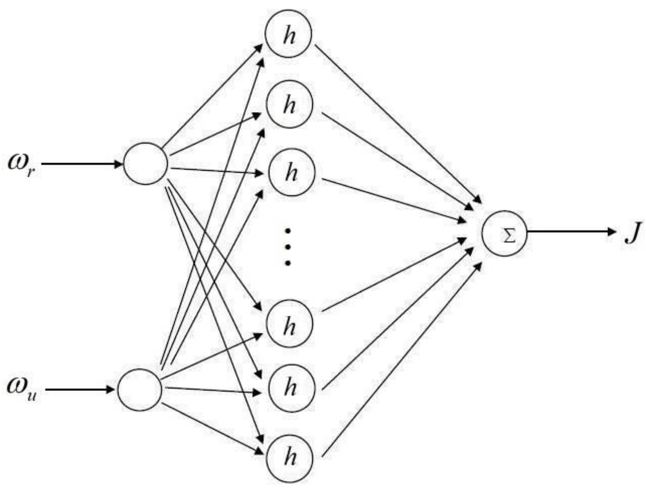

Fig. 2: Schematic diagram of RBF neural network

Define W as ideal weight and $\hat{W}$ as estimation of W. Error of weight as:

$$\tilde{W} = \hat{W} - W \quad (26)$$

Then, J and $\hat{J}$ can be writen as:

$$J = W^T \underline{h}, \quad \hat{J} = \hat{W}^T \underline{h}$$
$$\tilde{J} = \hat{J} - J = \tilde{W}^T h \tag{27}$$

Where $\underline{h}$ is the vector output of the hidden layer with its transfer function defined as:

$$h_i = \frac{\exp\left(-\frac{\left\|\omega_u - c_{1i}\right\|^2 + \left\|\omega_r - c_{2i}\right\|^2}{b_i^2}\right)}{\sum_{j=1}^{n} \exp\left(-\frac{\left\|\omega_u - c_{1i}\right\|^2 + \left\|\omega_r - c_{2i}\right\|^2}{b_j^2}\right)}$$

Where n is the number neural of neural network. With uncertain elements, control signals that are derterminded in the above section are rewritten as:

$$\hat{\tau}_u = -\frac{1}{\hat{c}_3}\left(\hat{c}_1\omega_u + \hat{c}_2 T - \dot{\omega}_{ud} + k_2 \text{sat}(S_u)\right) \tag{28}$$

$$\hat{\tau}_r = -\frac{1}{\hat{c}_9}\left(\hat{c}_8\omega_r + \hat{c}_7 T - \dot{\omega}_{rd} + k_3 \text{sat}(S_r)\right) \tag{29}$$

Replace τ_u, τ_r in (15) and (16) by $\hat{\tau}_u$, $\hat{\tau}_r$ we obtain:

$$\dot{S}_u = \frac{\tilde{J}_u}{J_u}\dot{\omega}_{ud} - \frac{\hat{J}_u}{J_u} k_2 \text{sat}(S_u) \tag{30}$$

$$\dot{S}_r = \frac{\tilde{J}_r}{J_r}\dot{\omega}_{ur} - \frac{\hat{J}_r}{J_r} k_3 \text{sat}(S_r) \tag{31}$$

Proposing Lyapunov candidate function for S_u:

$$V_u = \frac{1}{2} J_u S_u{}^2 + \frac{1}{2} Tr\left(\tilde{W}_u{}^T F_u{}^{-1} \tilde{W}_u\right) \tag{32}$$

Where F_u is a fit positive matrix. Taking time derivative of (32),we have:

$$\dot{V}_u = \frac{1}{2}\dot{J}_u S_u{}^2 + J_u S_u \dot{S}_u + Tr\left(\tilde{W}_u{}^T F_u{}^{-1} \dot{\hat{W}}_u\right) \tag{33}$$

Replacing (30) in (33):

$$\dot{V}_u = \frac{1}{2}\dot{J}_u S_u{}^2 + J_u S_u \left(\frac{\tilde{J}_u}{J_u}\dot{\omega}_{ud} - \frac{\hat{J}_u}{J_u} k_2 sat(S_u)\right) + Tr\left(\tilde{W}_u{}^T F_u{}^{-1} \dot{\hat{W}}_u\right)$$

$$\dot{V}_u = \frac{1}{2}\dot{J}_u S_u{}^2 - \hat{J}_u k_2 S_u \text{sat}(S_u) + Tr\left(\tilde{W}_u{}^T \left(F_u{}^{-1}\dot{\hat{W}}_u + h\dot{\omega}_{ud} S_u\right)\right)$$

Choosing updated law as:

$$\dot{\hat{W}}_u = -F_u h_u \dot{\omega}_{ud} S_u$$

$\dot{V}_u$ can be rewritten as:

$$\dot{V}_u = \frac{1}{2}\dot{J}_u S_u{}^2 - \hat{J}_u k_2 S_u sat(S_u)$$

Otherwise, $\dot{J}_u \le 0$, thus $\dot{V}_u \le 0$. Proposing the candidate Lyapunov function for S_r:

$$V_r = \frac{1}{2} S_r{}^2 + \frac{Tr\left(\tilde{W}_r{}^T F_r{}^{-1} \tilde{W}_r\right)}{2 J_r} \tag{34}$$

Where F_r is a fit positive matrix. Similarly, choosing updated law for weight as:

$$\dot{\hat{W}}_r = -F_r h_r \dot{\omega}_{rd} S_r$$

We obtain $\dot{V}_r$ below:

$$\dot{V}_r = -\frac{\hat{J}_r}{J_r} k_3 S^2{}_r - \frac{\dot{J}_r Tr\left(\tilde{W}_r^T F^{-1}{}_r \tilde{W}\right)}{2 J_r{}^2}$$

Otherwise, $\dot{J}_r \ge 0$, thus $\dot{V}_r \le 0$.

IV. SIMULATION RESULT

In this section, the performance of the proposed controller is demonstrated through a numerical simulation. To adequately evaluate the effectiveness of the control system, the reference web speed of rewinding is changed in two cases mentioned in Fig. 3 and Fig. 4.

The parameters of the roll to roll system are utilized in simulation can be listed as follow: $R_{u0} = 0.04\text{m}$; $R_{r0} = 0.015\text{m}$; $J_{u0} = J_{r0} = 1\text{kg/m/s}$; $L = 0.3\text{m}$; $K = 200\text{kg/m}$; $B_u = B_r = 0.00002533\text{kgms/rad}$; $h = 0.00002\text{m}$; $w = 1\text{m}$.

The parameters of the controller are chosen as: $\lambda_1 = \lambda_2 = 0.01$; $c_1 = 5$; $c_2 = 10$; $c_3 = 10$.

In the simulation, we compare the performance of the BSM controller to the adaptive RBFN-BSM controller. Fig. 2 and Fig. 3 describe the actual speed of rewind and the tension with the change of the reference speed of rewind in time and the desired web tension $T_{ref} = 2\,\text{N}$.

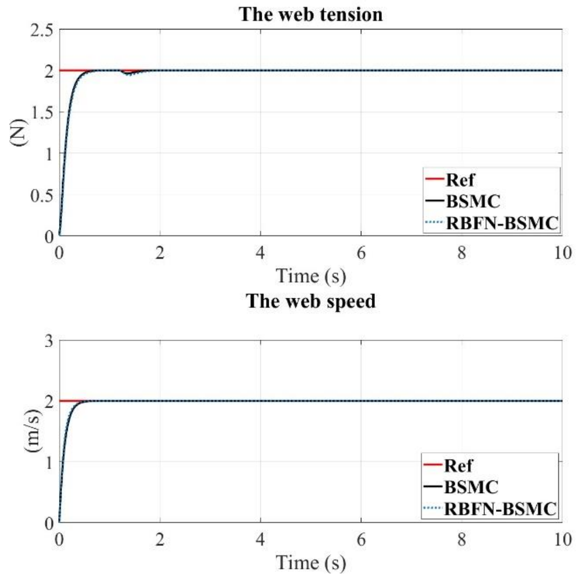

Fig. 3: The web tension and speed responses of rewinding roll.

In order to demonstrate tracking ability of the proposed control, the desired speed is required to change from 2m/s to 3m/s.

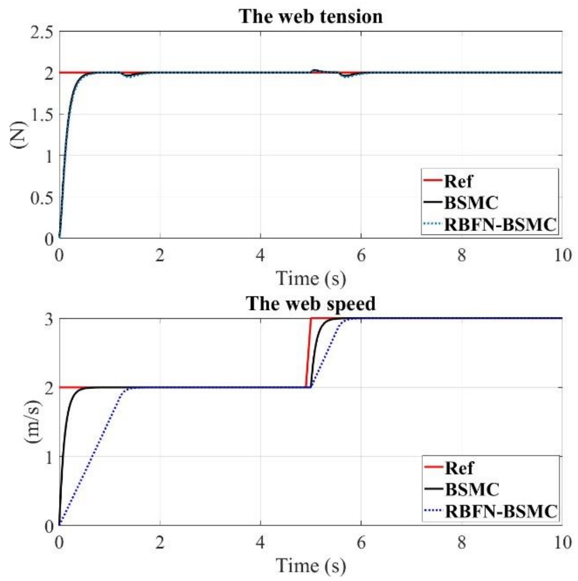

Fig. 4: The web tension and speed responses of rewinding roll.

As shown in Fig. 3 and Fig. 4, both the BSMC and the RBFN-BSMC schemes ensure the quality of the roll to roll system. From the result in Fig. 4, the web speed tends to the reference value after approximately 1 second, this time is kept in allowed time. Moreover, BSMC receives full information of the web transport system while RBFN-BSMC must estimate the information of model. Therefore, the performance of the BSMC method shows better quality in comparison with RBFN-BSMC responses. However, the full information of the roll to roll model is difficult to achieve in practice, thus RBFN-BSMC law shows the good ability in industrial application rather than BSMC.

V. CONCLUSION

In this paper, we have proposed the controller by combining backstepping method with sliding mode control for the web transport systems, in which, the estimator based on RBF neural is utilized for approximating system uncertainties. The simulation results show that the control system achieves both tracking and adaptation performances. Furthermore, using RBF neural, the controller does not require the precise description of plant, thus the proposed controller is highly capable to use in various industrial applications.

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