Web Tension Observer Based Control for Single-Span Roll to Roll Systems

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Abstract. Roll-to-roll (R2R) systems show great potential for high-throughput and cost-effective production of flexible electronics, including solar cells, wearable sensors, and so on. Actually, most of design methods for tension control-ler of web transport system (such as paper, plastic film, etc.) require state variables as feedback. These variables can be measured directly using the sensors. However, the complex systems that have many states will require many sensors which makes the control system bulky and expensive. Moreover, direct measurements are difficult or tend to be inaccurate in many systems. In R2R systems, precise regulation of span tension is critical to ensure product quality. Elevated tension causes web fracture during operation; depressed or highly variable tension leads to irregular and unacceptable spool. The approach in this paper is to model the state observer with only a small number of sensors. Then, we will propose a method to build tension controller based on backstepping controller using the tension observer. Simulation has shown that the proposed controllers with tension observer well-perform against the inertia disturbances.

Keywords: Web Tension Control, Roll to Roll System, Sensorless, Tension Observer, Backstepping controller, Lyapunov Stability

1 Introduction

Web transport systems are currently very popular in the industry. A wide variety of consumer products are made from web materials such as paper, celluloid film, textiles and even some electronics. After being processed, web is rolled up into big rolls. Then, it will be taken into the web-handling machines (R2R) for subdivision, or printing ... The R2R which is one of the complex electromechanical systems is strong nonlinear, affected by different types of noise, especially when the system is operating at high speed [1]. In order to control this system, it is of importance to build an appropriate algorithm for the system. There has been an enormous number of researches based on the dynamics model of the system [2-5]. When controlling the system, it is vital to remain tension force in a designed value [3] to ensure the quality of materials which are not crumpled, broken or distorted, etc. A variety of algorithms are introduced, including backstepping [4], [5]. During the tension control process, it is necessary to acquire different state variables and various system parameters. With the R2R system, the moment of inertia of the unwinding and rewinding rolls varies greatly during operation, hence the estimation of how the moment of inertia directly affects the speed and quality of the systems is studied [6, 7]. In particular, there has been a great number of difficulties with sensor mounting, calibrating, etc. during the web tension measuring process. There are also in-depth researches on implementing feedback control based on the observation set [8, 9]. However, with a complex system such as R2R, a multi-roll system can have many spans and requires multiple sensors to measure force from the segments [10]. The development of controllers along with state observer that reduce the complex structure of hardware is necessary. In this paper, the controller are constructed based on a backstepping technique [11, 12]. In addition, the paper is also proposed a novel control scheme integrated with a tension observer. The tension observer is developed based on the tension dynamics. The simulation results exhibit excellent tension observability.

2 Tension observer base on backstepping controller

2.1 Modeling of R2R with single-span

A R2R includes several types of mechanical components (e.g., rollers, rolls, measuring devices, driving motors, etc.) and web spans. The R2R model consists of an unwind and a rewind roll, the axis of each roll is mounted and controlled by the torque of 2 motors, M_u and M_r as Fig.1. In this paper, it is assumed that the idler inertia is ignored, and the system is single-span.

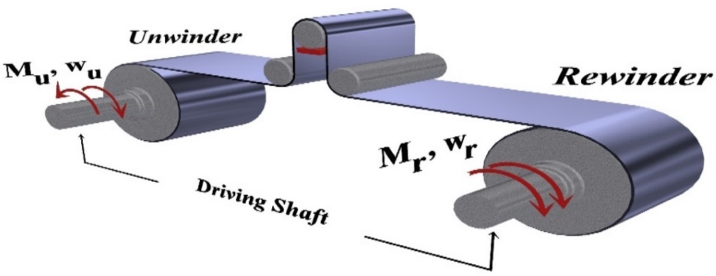

Fig. 1. Structure of a R2R with one processing section

$$\dot{T} = \frac{E.S}{L} R_r.w_r - \frac{2.E.S}{L} R_u.w_u - \frac{T}{L} R_r.w_r \quad (1)$$

$$\dot{w}_u = \frac{1}{J_u}.M_u + \frac{R_u}{J_u}.T - \frac{C_u}{J_u}.w_u \quad (2)$$

$$\dot{w}_r = \frac{1}{J_r}.M_r - \frac{R_r}{J_r}.T - \frac{C_r}{J_r}.w_r \quad (3)$$

where angular velocities and radiuses are calculated by the following equations:

$$\theta_u = \int_o^t w_u;\ \theta_r = \int_o^t w_r;\ R_u = R_{uo} - h\frac{\theta_u}{2\pi};R_r = R_{ro} + h\frac{\theta_r}{2\pi};$$

$$J_u = J_{uo} + \pi\rho d\,\frac{(R_u{}^4 - R_{uo}{}^4)}{4};J_r = J_{ro} + \pi\rho d\,\frac{(R_r{}^4 - R_{ro}{}^4)}{4}$$

Detailed explanation of the system parameters is given in Table 1 as follows:

Table 1. The system parameters

Parameters		Units
R_u; R_{u0}	Operating radius and initial radius of the unwind roll	m
R_r;R_{r0}	Operating radius and Initial radius of the rewind roll	m
J_u;J_{u0}	Total moment and initial total moment of unwinding inertia	kgm^2
J_r;J_{r0}	Total moment and initial total moment of rewinding inertia	kgm^2
w_u;w_r	Angular velocity of the unwind and rewind roll	rad/s
θ_u;θ_r	Rotational angular of the unwind and rewind roll	rad
c_u; c_r	Coefficient of vicious friction of the unwind and rewind roll	Nms
M_u;M_r	Torque applied to the unwind and rewind roll	Nm
T;L	Web tension and total length of web	N; m
E	Elasticity of web	N/m^2
S	Cross sectional area of web	m^2
h;d	The thickness of web and the width of web	m
ρ	The density of web	kg/m^3

The equations (1), (2) and (3) can be rewritten as follows:

$$\dot{\mathrm{T}} = \mathrm{c_4 w_u + c_5 T w_r + c_6 w_r} \quad (4)$$

$$\dot{\mathrm{w}}_\mathrm{u} = \mathrm{c_1 w_u + c_2 T + c_3 M_u} \quad (5)$$

$$\mathrm{w_r = c_7 T + c_8 w_r + c_9 M_r} \quad (6)$$

Where: $c_1 = \frac{C_u}{J_u}, c_2 = \frac{R_u}{J_u}, c_3 = -\frac{1}{J_u}, c_4 = -KR_u, c_5 = -\frac{Rr}{L}, c_6 = KR_r, c_7 = \frac{R_r}{Jr}, c_8 = -\frac{C_r}{J_r}, c_9 = \frac{1}{J_r}. K = \frac{ES}{L}$.

2.2 Controller design

The controller aims to keep the R2R tension and speed at the desired values. This section uses the sliding algorithm based on backstepping technique to design the controller. Firstly, we define the tracking error variables as bellows:

$$\bar{T} = T - T_d \;\; ;\overline{\mathrm{w}}_\mathrm{u} = \mathrm{w_u - w_{ud}};\; \overline{\mathrm{w}}_\mathrm{r} = \mathrm{w_r - w_{rd}}$$

Next, determining control signal such that web tension tracks the desired value. To regulate the error $\bar{T} \to 0$, choosing w_{ud} as:

$$\mathrm{w_{ud}} = -\frac{1}{\mathrm{c_4}}(\mathrm{c_5 T w_r + c_6 w_r + K_T \bar{T}}) \quad (7)$$

where K_T is a positive gain. The Lyapunov candidate function is chosen as:

$$V_T = \frac{1}{2}\bar{T}^2 \quad (8)$$

Using (4) and taking time derivative of (8) we obtain:

$$\dot{\mathrm{V}}_\mathrm{T} = \bar{\mathrm{T}}(\mathrm{c_4 w_u + c_5 T w_r + c_6 w_r}) \quad (9)$$

Next, replacing $w_u$by w_{ud} that is determined in (7) results in:

$$\dot{V}_T = -K_\mathrm{T}\bar{T}^2 \leq 0 \quad (10)$$

Base on backstepping technique, we will determine control signal M_u,M_r in order to $w_u$track w_{ud} and w_r track w_{rd}. From (5), (6) and (8), (9) we obtain error equations:

$$\dot{\overline{\mathrm{w}}}_\mathrm{u} = \mathrm{c_1 w_u + c_2 T + c_3 M_u} - \dot{\mathrm{w}}_\mathrm{ud} \quad (11)$$

$$\dot{\overline{\mathrm{w}}}_\mathrm{r} = \mathrm{c_8 w_r + c_7 T + c_9 M_r} - \dot{\mathrm{w}}_\mathrm{rd} \quad (12)$$

Proposing Lyapunov candidate function as:

$$\mathrm{V} = \frac{1}{2}\bar{T}^2 + \frac{1}{2}\overline{\mathrm{w}}_\mathrm{u}{}^2 \quad (13)$$

Differentiating (16) and using (11) và (5) gives:

$$\dot{\mathrm{V}} = -K_{\mathrm{T}}\bar{T}^2 + \mathrm{c}_4\bar{T}\bar{\mathrm{w}}_{\mathrm{u}} + \bar{\mathrm{w}}_{\mathrm{u}}(\mathrm{c}_1\mathrm{w}_{\mathrm{u}} + \mathrm{c}_2\mathrm{T} + \mathrm{c}_3\mathrm{M}_{\mathrm{u}} - \dot{\mathrm{w}}_{\mathrm{ud}}) \tag{14}$$

The control signal is calculated as:

$$\mathrm{M}_{\mathrm{u}} = -\frac{1}{\mathrm{c}_3}(\mathrm{c}_1\mathrm{w}_{\mathrm{u}} + \mathrm{c}_2\mathrm{T} + \mathrm{c}_4\bar{T} - \dot{\mathrm{w}}_{\mathrm{ud}} + K_{\mathrm{u}}\bar{\mathrm{w}}_{\mathrm{u}}) \tag{15}$$

Next, replacing $M_u$that is determinded in (17) results in:

$$\dot{\mathrm{V}} = -\mathrm{K}_{\mathrm{T}}\bar{T}^2 - K_{\mathrm{u}}\bar{\mathrm{w}}_{\mathrm{u}}{}^2 \leq 0 \tag{16}$$

Similarly, the control signal M_r is generated:

$$\mathrm{M}_{\mathrm{r}} = -\frac{1}{\mathrm{c}_9}(\mathrm{c}_8\mathrm{w}_{\mathrm{r}} + \mathrm{c}_7\mathrm{T} - \dot{\mathrm{w}}_{\mathrm{rd}} + K_{\mathrm{r}}\bar{\mathrm{w}}_{\mathrm{r}}) \tag{17}$$

Where systems parameters are defined in Table 2.

Table 2. The system parameters

Parameters		Units
w_{ud};w_{rd}	Desired angular velocity of the unwind and rewind roll	rad/s
M_{ud};M_{rd}	Desired torque applied to the unwind roll	Nm
T_d	Desired web tension	N
K_r; K_u	Shaft stiffness of the rewind and unwind motor	Nm/rad

2.3 Web tension observer

The tension observer is determined by

$$\dot{\hat{\mathrm{T}}} = \mathrm{c}_4\mathrm{w}_{\mathrm{u}} + \mathrm{c}_5\hat{\mathrm{T}}\mathrm{w}_{\mathrm{r}} + \mathrm{c}_6\mathrm{w}_{\mathrm{r}} \tag{18}$$

With this observer, the control signals (10), (19), (21) are rewritten to:

$$\hat{\mathrm{w}}_{\mathrm{ud}} = -\frac{1}{\mathrm{C}_4}\left(\mathrm{c}_5\hat{\mathrm{T}}\mathrm{w}_{\mathrm{r}} + \mathrm{c}_6\mathrm{w}_{\mathrm{r}} - \dot{\mathrm{T}}_{\mathrm{d}} + \mathrm{k}_{\mathrm{T}}(\hat{\mathrm{T}} - \mathrm{T}_{\mathrm{d}})\right) \tag{19}$$

$$\hat{\mathrm{M}}_{\mathrm{u}} = -\frac{1}{\mathrm{C}_3}\left(\mathrm{c}_1\mathrm{w}_{\mathrm{u}} + \mathrm{c}_2\hat{\mathrm{T}} + \mathrm{c}_4(\hat{\mathrm{T}} - \mathrm{T}_{\mathrm{d}}) - \dot{\hat{\mathrm{w}}}_{\mathrm{ud}} + \mathrm{k}_{\mathrm{u}}(\mathrm{w}_{\mathrm{u}} - \hat{\mathrm{w}}_{\mathrm{ud}})\right) \tag{20}$$

$$\hat{\mathrm{M}}_{\mathrm{r}} = -\frac{1}{\mathrm{C}_9}\left(\mathrm{c}_8\mathrm{w}_{\mathrm{r}} + \mathrm{c}_7\hat{\mathrm{T}} - \dot{\mathrm{w}}_{\mathrm{rd}} + \mathrm{k}_{\mathrm{r}}(\mathrm{w}_{\mathrm{r}} - \mathrm{w}_{\mathrm{rd}})\right) \tag{21}$$

Select the Lyapunov candidate function as follows:

$$V_{eu} = \frac{1}{2}(T - T_d)^2 + \frac{1}{2}(w_u - \hat{w}_{ud})^2 + \frac{1}{2}(\hat{T} - T)^2 \tag{22}$$

Differentiating (22) gives:

$$\dot{V}_{eu} = -k_T(T - T_d)^2 - k_u\left(w_u - \hat{w}_{ud}\right)^2 + c_5 w_r(\hat{T} - T)^2 - (k_T + c_5 w_r).(T - T_d)(\hat{T} - T) - (c_2 + c_4).\left(w_u - \hat{w}_{ud}\right)(\hat{T} - T) \tag{23}$$

Similarly, the control signal V_{er} is generated:

$$\mathrm{V}_{\mathrm{er}} = \frac{1}{2}\bar{\mathrm{w}}_{\mathrm{r}}{}^2 + \frac{1}{2}(\hat{\mathrm{T}} - \mathrm{T})^2 \tag{24}$$

Differentiating (24) gives:

$$\begin{aligned}\dot{V}_{er} &= \bar{\mathrm{w}}_{\mathrm{r}}(c_7 T + c_8 w_r + c_9\hat{M}_r - \dot{w}_{rd}) \\ &\quad + (\hat{T} - T)\left(\dot{\hat{T}} - c_4 w_u - c_5 T w_r - c_6 w_r\right) \\ &= -c_5 w_r\left((\hat{T} - T) - \frac{c_7}{2c_5 w_r}\bar{\mathrm{w}}_{\mathrm{r}}\right)^2 - \left(k_r + \frac{c_7{}^2}{4c_5{}^2 w_r{}^2}\right)\bar{\mathrm{w}}_{\mathrm{r}}{}^2\end{aligned} \tag{25}$$

then $\dot{V}_{er} < 0$.

3 Simulation results

The simulation reference values of the rewinding control system are shown in Table3. The simulation condition is set up with the zero initial conditions.

Table 3. Simulation parameters

Parameters	Values	Units
The width of web	0.25	m
The thickness of web	0.0002	m
Elasticity of web	$2{,}5.10^{9}$	N/m^2
Operating radius of the unwind roll	0,1	m
Operating radius of the rewind roll	0,05	m
Total moment of inertia of the unwind/rewind roll	$0.7.10^{-7}$	Kg/m/s
Coefficient of vicious friction of the unwind/rewind roll	$0.\ 25.\ 10^{-4}$	N.m.s
Shaft stiffness of the unwind motor	$5.e^{7}$	N.m

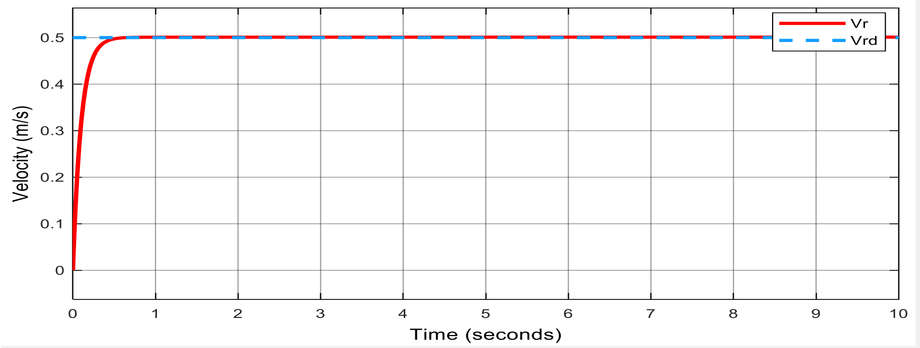

Fig. 2. Velocity response of R2R

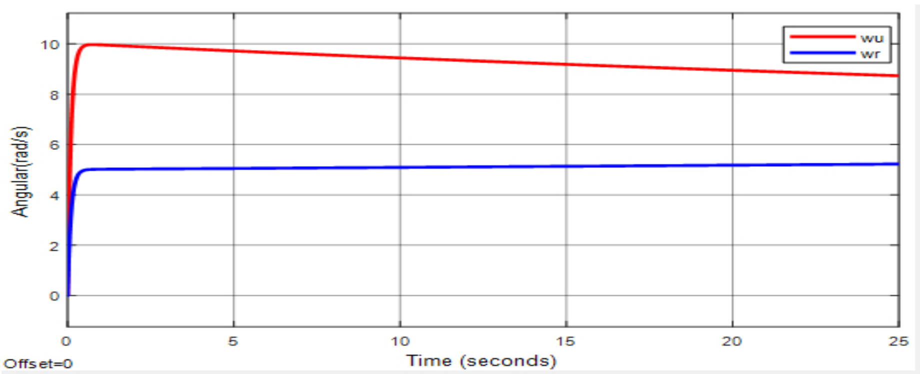

Fig. 3. Angular response of R2R

The value of rewinder velocity tracks the value of V_{rd}, does not exceed the adjustment, and deviation within the reasonable limits as Fig.2. The web velocity increases to the set value in a very short period of time, only 0.5s without overshoot. Fig.3 also indicates the angular speed at motor and rewinding-unwinding rolls sides that the angular speed of unwinding and rewinding section is kept stable at the reference value without overshoot with respect to the position reference of the web.

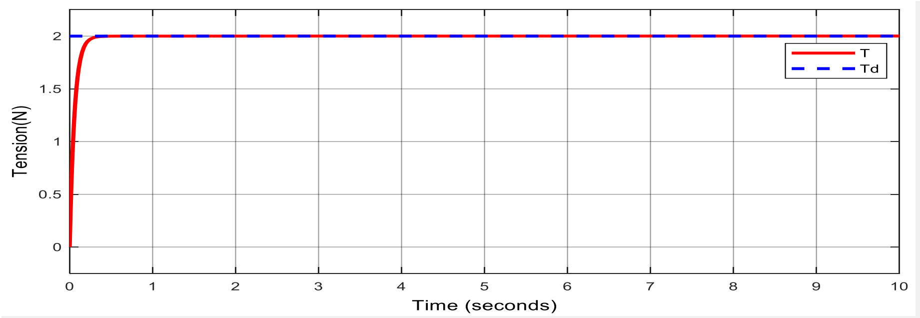

Fig. 4. T with T_d tension response

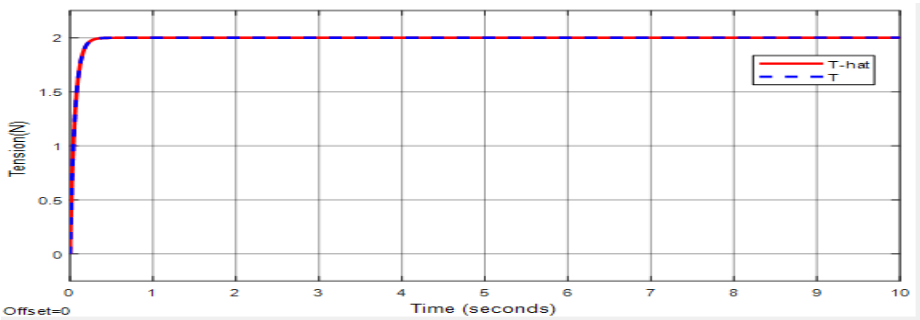

Fig. 5. T with the $\hat{T}$ tension response

The simulation results have clearly demonstrated that the tension T sticking to the desired tension T_d in a very short time of only about 0.15s Fig.4. Meet the tension output T, sticking to the tension value set $\hat{T}$ in a very short time of only about 0.15s as Fig.5. It shows that T tension has the same graph line as the $\hat{T}$ output from the observer, time for T and $\hat{T}$ to reach the set value is also very small, only about 0.15s, and there is no overshoot.

4 Conclusion

The paper successfully designs the tension sensorless based control for the R2R system. The closed loop system stability is proven through a set of Lyapunov functions. From the obtained results, without the tension sensor, web tension and velocity can be regulated precisely. The results also indicate that the proposed control algorithm can be generalized in multi-span roll to roll control systems. Experimental verification of the control will be conducted in the near future.

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