Velocity-Sensorless Decentralized Tension Control for Roll-to-Roll Printing Machines

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ABSTRACT This paper presents a velocity-sensorless decentralized tension control scheme without true machine parameter dependence for roll-to-roll printing machines. Both the nonlinear nature and parameter uncertainties are taken into account the development task. As the first merit, the proposed observer eliminates the requirement of velocity feedback without any plant information even the nominal parameters. The introduction of the active-damping with the estimated state reduces the closed-loop system order to 1 by the pole-zero cancellation using the specified feedback gains. Finally, the disturbance observer (DOB) replaces the regulation error integrators with the closed-loop robustness improvement against the high-frequency disturbances. The MATLAB/Simulink-based simulations validate the effectiveness of the proposed decentralized scheme.

INDEX TERMS Roll-to-roll printing machine, decentralized control, observer, pole-zero cancellation.

I. INTRODUCTION

Roll-to-roll (R2R) systems have been widely adopted for industrial manufacturing processes (e.g., in printing, drying, and coating). The unwinder and rewinder and nips provide the rolling actions to transport the web from the unwinder to the rewinder through nips to manufacture the various products, including films, metals, and textiles. There are two important control issues regulating the web velocity and tensions for each stage. The control law design task is not trivial and challenging because of the inherent dynamic nonlinearity and parameter changes according to the unexpected sudden fault and unwinder and rewinder inertia variations [1]–[4].

The two control strategies employed are called decentralized and centralized methods. For large-scale processes, preference has been to adopt the decentralized method, which regulates each agent using local measurement feedback. The interactions between local agents must be carefully considered to prevent performance degradation and instability. Traditionally, the decentralized scheme was implemented using the proportional-integral-derivative (PID) regulator with local measurement of web velocity and tension errors [5]. The PID gains were tuned by trial—and-error (Ziegler–Nicholas, Cohen—Coon, etc.) and Bode and Nyquist techniques using the linearized machine dynamics for a given operating condition. The resultant closed-loop performance could be limited using the fixed tuned gains resulting from changes in the operating condition [1], [5]–[7]. The web transport velocity causes dramatic winder inertia variations, resulting in performance degradation and instability. Online PID gain tuning techniques were presented using neural networks and fuzzy logic to optimize the cost function, thereby achieving significantly improved robustness despite the winder inertia variations [7]–[10]. A tension estimator based on the nonlinear observer design technique was proposed to lower implementation cost [11], [12]. The novel observer design techniques as in [13], [14] can be used as a solution to the web-velocity estimation problem by using only the lower and upper bounds of machine parameters. In [15], the recent nonlinear decentralized scheme using the output regulation method successfully showed the closed-loop robustness improvement against disturbance caused by the interactions between agents. The resultant controller forms the state-feedback and feed-forward compensation term.
Its target state and input trajectories solve the nonlinear differential-algebraic equations derived from R2R nonlinear dynamics via the proposed iteration technique. Experimental data were also included to verify the practical advantages from the analysis results [15]. The optimal state-feedback technique was used to optimize the cost index by solving an optimization problem under constraints expressed as the system-parameter-dependent linear matrix inequality online [4]. The machine dynamics are decoupled into linear and nonlinear parts. The introduced feed-forward compensation terms canceled out the disturbances from nonlinear dynamics and state-feedback, with the optimal gain robustly stabilizing the whole system to the desired equilibrium point. The issue of parameter dependence can be addressed by adopting the recent real-time parameter estimation mechanism as in [16]–[20]. Sliding-mode and adaptive controls alleviated the parameter dependence level with the inclusion of dynamic compensators dominating or canceling out the disturbances in the feed-forward loop [21]–[23].

The centralized scheme can be applied for small- and medium-scale processes with a high computational performance controller. The availability of all agent measurements makes it possible to apply novel nonlinear multivariable approaches. In the controller design task, a simple additional compensator relying on other local agent measurements was included in the feed-forward loop to ensure closed-loop stability. Studies have also proposed optimal state-feedback [24], [25] and neural-network-based schemes [26] involving parameter dependence. The desired tension and web transport velocity references are automatically obtained to meet the predetermined web longitude regulation performance based on the full-state feedback differential flatness method [27].

The previous results including the centralized and decentralized scheme suffered from parameter dependence of control and observers, at least partially, which is the problem to be solved in this study. Herein, an advanced velocity-sensorless nonlinear tension control law under a decentralized structure without the requirement of full-state feedback and true system parameter values is presented. The advantages of the proposed decentralized controller are given as follows: (a) Parameter-independent velocity derivative observers are used to eliminate the requirement of velocity feedback for tension control. (b) A proportional-derivative (PD) tension control law includes observer-based active-damping for closed-loop system order reduction through a combination of specified PD gain and pole-zero cancellation. (c) A disturbance observer (DOB) is incorporated as a replacement for regulation error integral actions in the PD-type tension and proportional (P) web velocity controller to enhance the closed-loop robustness and to ensure the two beneficial properties of performance recovery and steady-state error rejection. MATLAB/Simulink software is used to emulate the closed-loop system using the S-function in the C language to demonstrate the effectiveness of the proposed controller.

A summary of the rest of the article is given as follows: Section II briefly describes the R2R system configuration and its nonlinear dynamics. The state estimation and control algorithms are presented in Section III. Section IV provides proofs of the beneficial properties by analyzing the closed-loop dynamics. The simulation results and discussion are included in Section V. Finally, Section VI concludes this article.

II. R2R MACHINE DYNAMICS

Fig. 1 visualizes the N-span R2R machine structure with rewinder, unwinder, and nips. The unwinder and rewinder radii are denoted as \( r_0 \) (m) and \( r_N \), respectively, with their core radii of \( r_{0,0} \) and \( r_{0,N} \), respectively. The coefficients \( L_i \) (in meters), \( i = 1, \ldots, N \), represent the lengths of each stage. The rewinder torque \( T_N \) (in Nm) adjusts the web moving velocity \( v_N \) (in m/s) and the tensions of each span, \( T_i \) (in newtons), \( i = 1, \ldots, N \), are controlled by the nip and unwinder torques \( u_{N-1}, u_{N-2}, \ldots, u_0 \). Therefore, the web velocity \( v_N \) and tensions \( T_i, i = 1, \ldots, N \), are treated as the state variables needed to be controlled by the design variables \( u_i, i = 0, 1, \ldots, N \) (motor torques).

This study considers the special case of \( N = 2 \) for the simplicity, which has one nip, unwinder, and rewinder. In this case, there are the three linear velocities for the unwinder, the nip, and the rewinder denoted as \( v_0, v_1, \) and \( v_2 \), whose dynamics are given by [23]:

\[
\dot{v}_0 = \frac{r_0}{J_0}u_0 + \frac{r_0^2}{J_0}T_1 - \frac{b_0}{J_0}v_0 + \left( \frac{\rho W t r_0^2}{2\pi r_0^2} - \frac{t_w}{2\pi r_0^2} \right)v_0^2, \\
\dot{v}_1 = \frac{r_1}{J_1}u_1 + \frac{r_1^2}{J_1}(T_2 - T_1) - \frac{b_1}{J_1}v_1, \\
\dot{v}_2 = \frac{r_2}{J_2}u_2 - \frac{r_2^2}{J_2}(T_2 - T_1) - \frac{b_2}{J_2}v_2 + \left( \frac{\rho W t r_2^2}{2\pi r_2^2} - \frac{t_w}{2\pi r_2^2} \right)v_2^2, \\
\forall \gamma \geq 0,
\]

with coefficients of \( b_i, i = 0, 1, 2 \) (friction, in kg m s/rad), \( \rho \) (web density, in kg/m³), \( W \) (web width, in meters), \( t_w \) (web thickness, in meters), \( r_1 \) (nip radius, in meters), and \( J_1 \) (nip inertia, in kg m²). The span tensions satisfy the relationships

\[
\dot{T}_1 = \frac{G}{L_1}(v_1 - v_0) + \frac{1}{L_1}T_0v_0 - \frac{1}{L_1}T_1v_1, \\
\dot{T}_2 = \frac{G}{L_2}(v_2 - v_1) + \frac{1}{L_2}T_1v_1 - \frac{1}{L_2}T_2v_2.
\]
∀ t ≥ 0, with G and T₀ being the wound-up tension of unwinding roll (in newtons) and the Young’s modulus multiplied by the web cross-sectional area (in newtons), respectively. The unwinder and rewinder radii are governed by

\[ \dot{r}_0 = -\frac{r_w v_0}{2\pi r_0}, \quad \dot{r}_2 = \frac{r_w v_2}{2\pi r_2}, \quad \forall t \geq 0. \tag{6} \]

The unwinder and rewinder inertias J₀ and J₂ (in kg m²) vary according to the following rules:

\[ J_0 = J_{0,0} + \frac{1}{2} \pi \rho W(r_o^4 - r_o^4), \tag{7} \]

\[ J_2 = J_{2,0} + \frac{1}{2} \pi \rho W(r_o^4 - r_o^4), \quad \forall t \geq 0, \tag{8} \]

with the unwinder and rewinder bare inertias of J₀,₀ and J₂,₀.

This study focuses on devising the tension and web velocity control scheme for the 2-span machine for simplicity since the result for the 2-span system can be trivially expanded to this general case. See [27] for the N-span system dynamics.

### III. CONTROL ALGORITHM

The first-order system in the form of low-pass filter (LPF) is adopted for the target velocity and tension performances; that is

\[ \dot{v}_s^\prime = \omega v_2 (v_2,ref - v_s^\prime), \quad \dot{T}_s^\prime = \alpha r_0 (T_1,ref - T_s^\prime), \tag{9} \]

∀ t ≥ 0, with the constant references v₂,ref and T₁,ref and cut-off frequencies \( \omega v_2 \) and \( \alpha r_0 \), i = 1, 2. This section gives the decentralized control algorithm shown in Fig. 2 to ensure the control objective:

\[ \lim_{t \to \infty} v_2 = v_2^*, \quad \lim_{t \to \infty} T_i = T_i^*, \quad i = 1, 2, \tag{10} \]

exponentially; this is referred to as performance recovery in the rest of this article. See Section IV for the closed-loop analysis.

![FIGURE 2. Decentralized 2-span R2R control system structure.](image)

First, slight modifications of velocity and tension dynamics are made with nominal parameters (·)o. For velocity dynamics,

\[ \dot{v}_0 = \frac{r_0^o}{J_0^o} u_0 + \phi_0 + d_0, \tag{11} \]

\[ \dot{v}_1 = \frac{r_1^o}{J_1^o} u_1 + \phi_1 + \left(\frac{r_2^o}{J_1^o}\right)^2 \dot{T}_1 + d_1, \tag{12} \]

\[ \dot{v}_2 = \frac{r_2^o}{J_2^o} u_2 + \phi_2 + \left(\frac{r_2^o}{J_2^o}\right)^2 \dot{T}_2 + d_2, \tag{13} \]

with \( r_0^o \) and \( r_2^o \) being the initial radii of the unwinder and the rewinder, respectively. \( J_0^o := \left| J_0 \right|_{r_0 = r_0^o} \), \( J_2^o := \left| J_2 \right|_{r_2 = r_2^o} \), lumped disturbances \( d_i \), i = 0, 1, 2, tension references \( T_1,ref \) and \( T_2,ref \), \( \dot{T}_1 := T_1,ref - T_1 \), and \( \dot{T}_2 := T_2,ref - T_2 \). The available signals are defined as \( \phi_0 := \left(\frac{r_0^o}{J_0^o}\right)^2 T_0 - \frac{L_0^o}{J_1^o} \dot{v}_0 \), \( \phi_1 := \left(\frac{r_2^o}{J_1^o}\right)^2 T_1 - \frac{L_1^o}{J_2^o} \dot{v}_1 \), and \( \phi_2 := \left(\frac{r_0^o}{J_2^o}\right)^2 \dot{T}_2 \).

For tension dynamics,

\[ \dot{T}_1 = \frac{T_0^o - G^o}{L_1^o}\dot{v}_0 + \frac{G^o}{L_1^o} v_1 - \frac{1}{L_1^o} T_1 v_1 + \tilde{d}_1, \tag{14} \]

\[ \dot{T}_2 = \frac{T_1,ref - G^o}{L_2^o} v_1 + \frac{G^o}{L_2^o} v_2 - \frac{1}{L_2^o} \tilde{T}_1 v_1 \]

\[ - \frac{1}{L_2^o} T_2 v_2 + \tilde{d}_2, \quad \forall t \geq 0, \tag{15} \]

with lumped disturbances \( \tilde{d}_1 \) and \( \tilde{d}_2 \). The second-order tension dynamics are obtained using the modified dynamics of (11)–(15) as

\[ \dot{T}_1 = g_{T_1} u_1 - \phi_1 + \tilde{d}_1, \quad i = 1, 2, \quad \forall t \geq 0, \tag{16} \]

with \( g_{T_1} := \frac{(T_0^o - G^o)^2}{L_1^o J_1^o}, \quad \phi_1 := \frac{(T_0^o - G^o)^2}{L_1^o J_1^o} \dot{v}_0, \quad g_{T_2} := \frac{(T_1,ref - G^o)^2}{L_2^o J_2^o}, \quad \phi_2 := \frac{(T_1,ref - G^o)^2}{L_2^o J_2^o} \dot{v}_1 \), and lumped disturbances \( d_1 := \frac{T_0^o - G^o}{L_1^o} \dot{v}_0 + \frac{G^o}{L_1^o} v_1 - \frac{1}{L_1^o} (\tilde{T}_1 v_1) + \tilde{d}_1 \) and \( d_2 := \frac{(T_1,ref - G^o)^2}{L_2^o} (\dot{v}_1) + \frac{G^o}{L_2^o} v_2 - \frac{1}{L_2^o} (\tilde{T}_1 v_1 + \tilde{T}_1 v_1) - \frac{1}{L_2^o} (T_2 v_2) + \tilde{d}_2 \).

### A. WEB VELOCITY CONTROL ALGORITHM

To eliminate the tension feedback, rewrite the rewinder velocity dynamics of (13) as

\[ \ddot{v}_2 = \frac{r_2^o}{J_2^o} (\omega v_2 - \phi_2 - \dot{\tilde{d}}_2), \quad \forall t \geq 0, \tag{17} \]

with the newly defined disturbance \( \dot{d}_v := \left(\frac{r_2^o}{J_2^o}\right)^2 \dot{T}_2 + d_2 \), whose stabilization can be obtained by the proposed control law

\[ u_2 = \frac{J_2^o}{J_2^o} (\omega v_2 - \phi_2 - \dot{\tilde{d}}_2), \quad \forall t \geq 0, \tag{18} \]

with the DOB

\[ \dot{\tilde{d}}_v = -L_v v_2 - L_v (\frac{r_2^o}{J_2^o} u_2 - \phi_2), \tag{19} \]

\[ \dot{\tilde{d}}_v = \varepsilon_v + l_v v_2, \quad l_v > 0, \quad \forall t \geq 0. \tag{20} \]

Fig. 3 shows the web velocity loop driven by the proposed control law.
The second-order open-loop system (16) is given by
\[
\dot{T}_{vi} = -I_{vi} z_{T_{vi}} - l^2_{vi} T_i, \quad i = 1, 2, \forall t \geq 0, \quad (21)
\]
\[
\hat{T}_i = z_{T_{vi}} + l_{ri} T_i, \quad l_{ri} > 0, \quad (22)
\]
This corresponds to a main merit of this study. Section IV analyzes the state estimation error convergence.

2) CONTROLLER
The proposed tension control law for stabilizing the second-order open-loop system (16) is given by
\[
u_{i-1} = \frac{1}{g_{T_i}}(-k_{dr_i} + \omega_{r_i})\hat{T}_i + k_{dr_i} \omega_{r_i} T_i - \phi_{T_i} - \hat{d}_T), \quad i = 1, 2, \forall t \geq 0, \quad (23)
\]
which does not involve in any plant parameters, not even nominal values. This subsection begins with an analysis of the disturbance estimate behavior in Lemma 1 for a simplification of the performance recovery proof.

Lemma 1: The disturbance estimate \( \hat{d}_v \) from the DOB (19)-(20) satisfies
\[
\dot{\hat{d}}_v = l_v (d_v - \hat{d}_v), \quad \forall t \geq 0, \quad (26)
\]
Proof: The output (20) gives
\[
\dot{\hat{d}}_v = -l_v (\hat{d}_v - l_v v_2) - l^2_v v_2 + l_v (-\frac{r^0}{J^2} u_2 - \phi_{v2}) + l_v \hat{v}_2 = l_v (d_v - \hat{d}_v), \quad \forall t \geq 0, \quad (27)
\]
with \( \Delta d_v := \hat{d}_v - d_v \). Theorem 1 proves the performance recovery described in (10) on the basis of result of Lemma 1.
Then, the closed-loop trajectories (27) and (29) give the time-to-state stability (ISS) and the inequality:

$$
\|x_v\| \leq e^{-\frac{\lambda}{2}} \|x_v(0)\|, \quad \forall t \geq 0, \forall \|e_d\| > \frac{2\Delta \bar{d}_v}{l_d}.
$$

(28)

with $\|\Delta \bar{d}_v\| \leq \Delta \bar{d}_v$ and $x_v(0)$ being the initial value of $x_v := [\bar{v}_2^T e_d^T]^T$.

Proof: It follows from the combination of (17) and (18)

$$
\dot{\bar{v}}_2 = -\omega_i \bar{v}_2 + e_d, \quad \forall t \geq 0.
$$

(29)

Now consider the positive-definite function:

$$
V_v := \frac{1}{2} \|x_v\|^2 \left( = \frac{1}{2} \|\bar{v}_2\|^2 + \frac{1}{2} \|e_d\|^2 \right), \quad \forall t \geq 0.
$$

Then, the closed-loop trajectories (27) and (29) give the time derivative of $V_v$ as

$$
\dot{V}_v = -\omega_i \bar{v}_2 \bar{v}_2 - \bar{v}_2 e_d - l_d e_d^2 + e_d \Delta \bar{d}_v
\leq -\frac{1}{2} x_v^T Q_v x_v - \frac{1}{2} \Delta \bar{d}_v (\|e_d\|^2 + 2 l_d)
\leq -\lambda_{min}(Q_v) V_v, \quad \forall t \geq 0, \forall \|e_d\| > \frac{2\Delta \bar{d}_v}{l_d},
$$

where $\lambda_{min}(Q_v)$ denotes the minimum eigenvalue of positive-definite matrix $Q_v := \left[ \begin{array}{cc} 2\omega_i & 0 \\ 0 & l_d \end{array} \right]$. This indicates the ISS with respect to $\Delta \bar{d}_v$ and the result (28) by the Comparison principle in [28].

From the result (28), it can be roughly concluded that

$$
\lim_{t \to \infty} v_2 = \bar{v}_2,
$$

exponentially, for sufficiently large value $l_d > 0$. The absence of regulation error integral actions in the proposed control law (18) leads to steady-state error issues in actual implementations, which can be cleared using the first-order disturbance estimation dynamics proved in Lemma 1. See Theorem 2 for details.

**Theorem 2:** The web velocity loop driven by the control law (18) and DOB (19) and (20) always attain their steady-state error issues in actual implementations, i.e., $v_2(\infty) = v_{2,ref}(\infty)$.

Proof: The closed-loop velocity and DOB dynamics (29) and (26) always attain their steady state:

$$
0 = A_{ss,v} x_{ss,v},
$$

(30)

with $x_{ss,v} := \left[ \begin{array}{c} \bar{v}_2(\infty) \\ e_d(\infty) \end{array} \right]^T$ and $A_{ss,v} := \left[ \begin{array}{cc} \omega_i & 1 \\ 0 & l_d \end{array} \right]$. The full-rankness of matrix $A_{ss,v}$ implies that $x_{ss,v} = 0$, from which it can be concluded that $v_2(\infty) = v_{2,ref}(\infty)$. "

**B. TENSION LOOP**

This subsection begins with an analysis of the state and disturbance estimate behavior in Lemmas 2 and 3 for a simplification of the performance recovery proof.

**Lemma 2:** The state estimate $\hat{T}_v$ from the observer (21) and (22) satisfies

$$
\dot{\hat{T}}_v = l_{T_v}(T_v - \hat{T}_v), \quad \forall t \geq 0.
$$

(31)

Proof: The observer output (22) gives

$$
\dot{\hat{T}}_v = -l_{T_v}(\hat{T}_v - T_v) - l_{T_v}^2 T_v + l_{T_v} \hat{T}_v
= l_{T_v}(T_v - \hat{T}_v), \quad \forall t \geq 0,
$$

with the observer dynamics (21) and definition $T_{vi} := \hat{T}_i$, which completes the proof.

The state variable $T_v$ can be decomposed as $T_v = T_{v,DC} + T_{v,AC}$ with $T_{v,DC}$ and $T_{v,AC}$ being its steady-state and transient components. Then, the result (31) implies that

$$
\dot{e}_{T_{v}} = -l_{T_v} e_{T_{v}} + \Delta T_v, \quad \forall t \geq 0,
$$

(32)

with $\Delta T_v := \hat{T}_{v,AC}$, which is used for following analysis.

**Lemma 3:** The disturbance estimate $\hat{d}_{T_i}$ from the DOB (24) and (25) satisfies

$$
\dot{\hat{d}}_{T_i} = l_{d_{T_i}}(d_{T_i} - \hat{d}_{T_i} + l_{T_v} e_{T_{v}}), \quad \forall t \geq 0.
$$

(33)

Proof: The output (25) gives

$$
\dot{\hat{d}}_{T_i} = -l_{d_{T_i}}(\hat{d}_{T_i} - \hat{d}_{T_v}) + l_{d_{T_i}} l_{T_v} e_{T_{v}}
-l_{d_{T_i}} l_{T_v} e_{T_{v}} - l_{d_{T_i}} \hat{d}_{T_v}
= l_{d_{T_i}}(\hat{T}_i - g_{T_v} u_{i-1} - \phi_{T_v} - \hat{d}_{T_v}) - l_{d_{T_i}} \hat{e}_{T_{v}}
= l_{d_{T_i}}(d_{T_i} - \hat{d}_{T_i}) + l_{d_{T_i}} l_{T_v} e_{T_{v}}, \quad \forall t \geq 0.
$$
with the DOB dynamics (24), open-loop dynamics (16), and error dynamics (32), which completes the proof.

The disturbance $d_{Ti}$ can be decomposed as $d_{Ti} = d_{Ti,DC} + d_{Ti,AC}$ with $d_{Ti,DC}$ and $d_{Ti,AC}$ being its steady-state and transient components. Then, the result (33) implies that

$$\dot{e}_{d_{Ti},F} = -l_{d_{Ti}}e_{d_{Ti},F} - l_{d_{Ti}}r_{Ti}e_{Ti} + \Delta d_{Ti}, \quad \forall t \geq 0,$$  

(34)

with $\Delta d_{Ti} := d_{Ti,AC}$, which is used for following analysis.

A main contribution of this study is the closed-loop system order reduction by the pole-zero cancellation from the specified feedback gain. Lemma 4 handles this issue.

Lemma 4: The tension loop driven by the proposed control law (23) renders the tension response to be

$$\tilde{T}_i = \omega_{Ti}\tilde{T}_i + e_{d_{Ti},F} + e_{r_{Ti},F},$$  

(35)

with the LPFs

$$\dot{e}_{d_{Ti},F} = -c_1e_{d_{Ti},F} + c_2e_{d_{Ti}},$$  

(36)

$$\dot{e}_{r_{Ti},F} = -c_1e_{r_{Ti},F} + c_2e_{r_{Ti}}, \quad \forall t \geq 0.$$  

(37)

for some $c_i > 0, i = 1, 2, 3.$

Proof: The combination of (16) and tension control law (23) gives

$$\dot{\tilde{T}_i} = -k_{d_{Ti}}\tilde{T}_i + \omega_{Ti}(\tilde{T}_{i,ref} - \tilde{T}_i) + k_{d_{Ti}}\omega_{r_{Ti}}\tilde{T}_i + e_{d_{Ti}}$$

$$= -k_{d_{Ti}}\tilde{T}_i + \omega_{Ti}(\tilde{T}_{i,ref} - \tilde{T}_i) + (k_{d_{Ti}} + \omega_{Ti})e_{r_{Ti}}, \quad \forall t \geq 0,$$  

(38)

and its Laplace transform is given by

$$(s^2 + (k_{d_{Ti}} + \omega_{Ti})s + k_{d_{Ti}}\omega_{r_{Ti}})T_i(s) = \omega_{Ti}(s + k_{d_{Ti}})T_{i,ref}(s) + E_{d_{Ti}}(s) + (k_{d_{Ti}} + \omega_{Ti})E_{r_{Ti}}(s), \quad \forall s \in \mathbb{C}.$$  

This can be simplified by pole-zero cancellation with the factorization of $(s^2 + (k_{d_{Ti}} + \omega_{Ti})s + k_{d_{Ti}}\omega_{r_{Ti}}) = (s + \omega_{Ti})(s + k_{d_{Ti}})$ to

$$(s + \omega_{Ti})T_i(s) = \omega_{Ti}T_{i,ref}(s) + E_{d_{Ti}}(s) + E_{r_{Ti}}(s),$$  

with $E_{d_{Ti}}(s) = \frac{1}{s+k_{d_{Ti}}}E_{d_{Ti}}(s)$ and $E_{r_{Ti}}(s) = \frac{k_{d_{Ti}} + \omega_{Ti}}{s+k_{d_{Ti}}}E_{r_{Ti}}(s).$ This completes the proof by the inverse Laplace transform.  

Now, Theorem 3 asserts the performance recovery described in (10) by deriving the whole control system dynamics on the basis of results of Lemmas 2–4.

Theorem 3: The tension loop driven by the proposed control law (23), observer (21) and (22), and DOB (24) and (25) guarantees the ISS and the inequality:

$$\|x_{Ti}\| \leq e^{-\frac{\lambda_i t}{2}}\|x_{Ti}(0)\|, \quad \forall t \geq 0,$$

$$\forall|e_{d_{Ti}}| > \frac{2\Delta\tilde{T}_i}{l_{d_{Ti}}}, \quad \forall|e_{r_{Ti}}| > \frac{2\Delta\tilde{T}_i}{l_{r_{Ti}}}$$  

(39)

with $|\Delta d_{Ti}| \leq \Delta\tilde{d}_{Ti}, |\Delta r_{Ti}| \leq \Delta\tilde{r}_{Ti},$ and $x_{Ti}(0)$ being the initial value of

$$x_{Ti} := \left[\tilde{T}_i \quad e_{d_{Ti},F} \quad e_{r_{Ti},F} \quad e_{d_{Ti}} \quad e_{r_{Ti}}\right]^T.$$  

Proof: It follows from the combination of (9) and (35) that

$$\dot{\tilde{T}_i} = -\omega_{Ti}\tilde{T}_i + e_{d_{Ti},F} - e_{r_{Ti},F}, \quad \forall t \geq 0.$$  

(40)

Now consider the positive-definite function:

$$V_{Ti} := \frac{1}{2}\|x_{Ti}\|^2 \geq 0,$$

$$\left(\frac{1}{2}(\tilde{T}_i^* + e_{d_{Ti},F}^2 + e_{r_{Ti},F}^2 + e_{d_{Ti}}^2 + e_{r_{Ti}}^2)\right)$$

Then, the closed-loop trajectories (32), (34), (36), (37), (40) give the time derivative of $V_{Ti}$ as

$$\dot{V}_{Ti} = \tilde{T}_i^*(\omega_{Ti}\tilde{T}_i^* - e_{d_{Ti},F} - e_{r_{Ti},F})$$

$$+ e_{d_{Ti},F}(c_2e_{d_{Ti},F} - c_2e_{d_{Ti}})$$

$$+ e_{r_{Ti},F}(c_2e_{r_{Ti},F} + c_2e_{r_{Ti}})$$

$$+ e_{d_{Ti}}(-l_{d_{Ti}}e_{d_{Ti}} - l_{d_{Ti}}r_{Ti}e_{r_{Ti}} + \Delta d_{Ti})$$

$$+ e_{r_{Ti}}(-l_{r_{Ti}}e_{r_{Ti}} + \Delta r_{Ti})$$

$$\leq -\frac{1}{2}x_{Ti}^TQ_{Ti}x_{Ti} - \frac{l_{d_{Ti}}}{2}\frac{\Delta \tilde{d}_{Ti}}{|e_{d_{Ti}}|}e_{d_{Ti}}^2$$

$$- \frac{l_{r_{Ti}}}{2}\frac{\Delta \tilde{r}_{Ti}}{|e_{r_{Ti}}|}e_{r_{Ti}}^2$$

$$\leq -\lambda_{min}(Q_{Ti})V_{Ti}, \quad \forall t \geq 0,$$

$$\forall|e_{d_{Ti}}| \geq 2\Delta\tilde{d}_{Ti}, \quad \forall|e_{r_{Ti}}| \geq 2\Delta\tilde{r}_{Ti}, \quad \forall t \geq 0,$$

where $\lambda_{min}(Q_{Ti})$ denotes the minimum eigenvalue of positive-definite matrix

$$Q_{Ti} := \begin{bmatrix} 2\omega_{Ti} & 2 & 2 & 0 & 0 \\ 2c_1 & 0 & -2c_2 & 0 \\ 0 & 2c_1 & 0 & -2c_3 \\ 0 & 0 & 2l_{r_{Ti}} & 2l_{d_{Ti}}l_{r_{Ti}} \\ 0 & 0 & 0 & l_{r_{Ti}} \end{bmatrix}.$$  

This indicates the ISS with respect to $\Delta d_{Ti}$ and $\Delta r_{Ti}$ and the result (39) by the Comparison principle in [28].

From the result (39), it can be roughly concluded that

$$\lim_{t \to \infty} T_i = T_{i}^{ss}, \quad i = 1, 2,$$

exponentially, for sufficiently large values $l_{d_{Ti}} > 0$ and $l_{r_{Ti}} > 0.$ The absence of regulation error integral actions in the proposed control law (23) leads to steady-state error issues in actual implementations, which can be cleared using the first-order state and disturbance estimation dynamics proved in Lemmas 2 and 3. For details, see Theorem 4.

Theorem 4: The tension loop driven by the proposed control law (23), observer (21) and (22), and DOB (24) and (25) always removes the steady-state errors in actual implementations, i.e., $T_i(\infty) = T_{i,ref}(\infty)$.

Proof: The closed-loop tension, observer, and DOB dynamics (38), (31), and (33) always attain their steady-state:

$$0 = A_{ss,T}x_{ss,T},$$
with $x_{sl,T} := \begin{bmatrix} T_l(\infty) e_{drl}(\infty) e_{Trl}(\infty) \end{bmatrix}^T$ and $A_{sl,T} := \begin{bmatrix} k_{drl} \omega_{rl} & 1 & k_{drl} + \omega_{rl} \\ 0 & l_{drl} & l_{drl} \omega_{rl} \\ 0 & 0 & l_{lr} \end{bmatrix}$. The full-rankness of matrix $A_{sl,T}$ implies that $x_{sl,T} = 0$, from which it can be concluded that $T_l(\infty) = T_{l,ref}(\infty)$.

V. SIMULATIONS

The nonlinear dynamics (1)–(6) with the real machine coefficients used [27] emulated the R2R machine behaviors using Simulink with the ODE45 solver. The following nominal parameters were used for controller implementation to realize the parameter variations: $t_w^o = 0.95 t_w$, $J_{o0}^o = 0.9 J_{o0}$, $J_{o2}^o = 1.3 J_{o2}$, $r_{o0}^o = 1.4 r_{o0}$, $r_{o2}^o = 1.2 r_{o2}$, $r_{i}^o = 0.9 r_i$, $\rho^o = 0.8 \rho$, $W^o = 1.2 W$, $G^o = 1.1 G$, $L_i^o = 1.2 L_i$, $L_2^o = 0.8 L_2$, $b_0^i = 0.85 b_0$, $b_1^i = 1.3 b_1$, $b_2^i = 1.2 b_2$, and $T_0^o = 0.6 T_0$. The proposed controller (21)–(25) was built using the level-2 S-function in the C language under the discrete-time setting with 1-ms sampling and control periods. The tuning result is summarized as follows: 1. velocity loop: (control) $f_{v_2} = 0.1$ Hz ($\omega_{v_2} = 2 \pi f_{v_2}$ rad/s) and (DOB) $f_{r_1} = 314$; 2. tension loop for $i = 1, 2$: (control) $f_{r_i} = 0.1$ Hz ($\omega_{r_i} = 2 \pi f_{r_i}$ rad/s), $k_{drl_i} = 180$, (observer) $l_{lr_i} = 30$, and (DOB) $l_{lr_i} = 250$.

The active-damping injection-based integral back-stepping (IBS) controller was adopted for a comparison study in which the additional active-damping design parameters, i.e., $b_{d,x} > 0$, $x = v_2, v_1, v_0, T_2$, and $T_1$, were included to enhance the robustness against the model-plant mismatches:

1) For the velocity loop,

$$u_2 = J_0^o \left(-b_{d,v_2} v_2 + \omega_{v_2} \tilde{v}_2 + k_{d,v_2} \omega_{v_2} \int_0^t \tilde{v}_2 d\tau\right).$$

2) For the span-1 tension loop,

$$v_{0,\text{ref}} = \frac{L_1^o}{T_1^o - G^o} \left(-b_{d,T_1} T_1 + \omega_{T_1} \tilde{T}_1\right) + b_{d,T_1} \omega_{T_1} \int_0^t \tilde{T}_1 d\tau,$$

$$u_0 = J_0^o \left(-b_{d,v_0} v_0 + \omega_{v_0} \tilde{v}_0 + b_{d,v_0} \omega_{v_0} \int_0^t \tilde{v}_0 d\tau - \phi_{v_0}\right),$$

$$\tilde{v}_0 = v_{0,\text{ref}} - v_0.$$

3) For the span-2 tension-loop,

$$v_{1,\text{ref}} = \frac{L_2^o}{T_{1,\text{ref}} - G^o} \left(-b_{d,T_2} T_2 + \omega_{T_2} \tilde{T}_2\right) + b_{d,T_2} \omega_{T_2} \int_0^t \tilde{T}_2 d\tau,$$

$$u_1 = J_0^o \left(-b_{d,v_1} v_1 + \omega_{v_1} \tilde{v}_1 + b_{d,v_1} \omega_{v_1} \int_0^t \tilde{v}_1 d\tau - \phi_{v_1}\right),$$

$$\tilde{v}_1 = v_{1,\text{ref}} - v_1, \forall t \geq 0,$$

with the well-tuned velocity-loop cut-off frequencies $f_{v_0} = f_{v_1} = 45$ (\omega_{v_0} = 2 \pi f_{v_0}$ and $\omega_{v_1} = 2 \pi f_{v_1}$). The active-damping coefficients were selected as $b_{d,v_2} = b_{d,v_1} = b_{d,v_0} = 8$, and $b_{d,T_2} = b_{d,T_1} = 10$ for the best performance. The web velocity and tension cutoff frequency values $\omega_{v_2}$ and $\omega_{r_i}, i = 1, 2$, were left to be identical to those of the proposed controller. Note that when using the active-damping injection-based IBS controller, the closed-loop system is governed by the desired LPF dynamics (9) based on pole-zero cancellation. Therefore, the two controllers (i.e., proposed and active-damping injection-based IBS controllers) share the same control objective.

A. TENSION TRACKING MODE

A pulse tension reference was applied from 50 to 100 N for three different web velocity operation modes of 0.5, 1, and 3 m/s. Figs. 6 and 7 show the comparison results, revealing a slight interference reduction from the proposed controller. A significant improvement in web velocity regulation performance was observed in Fig. 8 as a result of the improved high-frequency disturbance rejection performance of the DOB embedded in the proposed web velocity controller. As shown in Fig. 9, the tension loop observers successfully estimated the actual states, maintaining the estimation errors sufficiently small and near zero. Figs. 10 and 11 present the DOB responses that continuously estimated the undesirable disturbances to maintain the stability of the closed-loop system with the desired closed-loop performance.

B. TENSION REGULATION MODE: WEB VELOCITY VARIATION

The tension references were fixed to 50 N, and three difference pulse web velocity references were applied from 3 to 3.3, 3.5, and 4 m/s. The closed-loop tension responses
shown in Figs. 12 and 13 exhibit considerable over- and undershoot reduction and closed-loop stabilization from the proposed controller. However, the unwinder and rewinder inertia variations according to (7) and (8) destabilized the closed-loop system driven by the IBS owing to the absence of disturbance compensations by the DOB. Figs. 14–16 show the corresponding web velocity and DOB responses.

C. TENSION REGULATION MODE: WOUND-UP TENSION VARIATION

This simulation was performed three times for difference web velocity operation modes of 0.5, 1, and 3 m/s with...
a fixed tension reference of 50 N. The unwinding roll wound-up tension $T_0$ was suddenly increased from its initial value of 70 to 170 N, and it was then restored to its initial value. As shown in Figs. 17 and 18, the proposed controller effectively suppresses the tension over- and undershoots caused by the sudden wound-up tension changes, compared with the IBS controller. The combination of novel features, observer-based active damping, and DOBs led to this practical advantage.

![FIGURE 16. Web velocity-loop DOB responses under velocity tracking modes from 3 to 3.3, 3.5, and 4 m/s.](image)

![FIGURE 17. Span-1 tension regulation performance comparison with $v_s = 0.5, 1,$ and 3 m/s operation modes and wound-up tension changes of 70 $\rightarrow$ 170 $\rightarrow$ 70 N.](image)

![FIGURE 18. Span-2 tension regulation performance comparison with $v_s = 0.5, 1,$ and 3 m/s operation modes and wound-up tension changes of 70 $\rightarrow$ 170 $\rightarrow$ 70 N.](image)

VI. CONCLUSIONS

In this study, an advanced observer-based decentralized tension control technique was proposed with reduced parameter and sensor dependence. There were two main innovations: (a) the first-order velocity observers without requirement of any plant information, not even nominal parameter values and (b) the combination of estimated damping injection, pole-zero cancellation technique, and DOBs offering useful closed-loop properties and performance recovery while being offset-free. The convincing numerical data from various simulations validated the practical merits of the proposed technique. This result can be applied to multi-machine synchronization applications with a systematic controller tuning technique and experimental data.

REFERENCES

[1] R. Pagilla and D. Knittel, “Recent advances in Web longitudinal control,” in Proc. 8th Int. Conf. Web Handling, Stillwater, OK, USA, 2005, pp. 255–274.
[2] J. Lee and C. Lee, “Model-based winding tension profile to minimize radial stress in a flexible substrate in a Roll-to-Roll Web transporting system,” IEEE/ASME Trans. Mechatronics, vol. 23, no. 6, pp. 2928–2939, Dec. 2018.
[3] Y.-M. Choi, D. Kang, S. Lim, M. G. Lee, and S.-H. Lee, “High-precision printing force control system for Roll-to-Roll manufacturing,” IEEE/ASME Trans. Mechatronics, vol. 22, no. 5, pp. 2351–2358, Oct. 2017.
[4] H. Hou, X. Nian, H. Xiong, Z. Wang, and Z. Peng, “Robust decentralized coordinated control of a multimotor Web-winding system,” IEEE Trans. Control Syst. Technol., vol. 24, no. 4, pp. 1495–1503, Jul. 2016.
[5] K.-H. Shin, Tension Control, New York, NY, USA: Tappi Press, 2000.
[6] W. Wolfkemmer, “Tension control of webs—a review of the problems and solutions in the present and future,” in Proc. 3rd Int. Conf. Web Handling, Stillwater, OK, USA, 1995, pp. 198–229.
[7] G. Ponniah, M. Zubair, Y.-H. Doh, and K.-H. Choi, “Fuzzy decoupling to reduce propagation of tension disturbances in roll-to-roll system,” Int. J. Adv. Manuf. Technol., vol. 71, nos. 1–4, pp. 153–163, Mar. 2014.
[8] K. Okada and T. Sakamoto, “An adaptive fuzzy control for Web tension control system,” in Proc. 24th Annu. Conf. IEEE Ind. Electron. Soc., Aug./Sep. 1998, pp. 1762–1767.
[9] F. L. Luo, “Multiple-page-mapping backpropagation neural network for constant tension control,” IEEE Trans. Electr. Power Appl., vol. 145, no. 3, pp. 239–245, 1998.
[10] F. Janabi-Sharifi, “A neuro-fuzzy system for looper tension control in rolling mills,” Control Eng. Pract., vol. 13, no. 1, pp. 1–13, Jan. 2005.
[11] S.-H. Song and S.-K. Sul, “A new tension controller for continuous strip processing line,” IEEE Trans. Ind. Appl., vol. 36, no. 2, pp. 633–639, Mar./Apr. 2000.
[12] V. Gassmann and D. Knittel, “Robust PI-LPV tension control with elasticity observer for Roll-to-Roll systems,” in Proc. 18th IFAC World Congr., 2011, pp. 8639–8644.
[13] J. Yao and W. Deng, “Active disturbance rejection adaptive control of uncertain nonlinear systems: Theory and application,” Nonlinear Dyn., vol. 89, no. 3, pp. 1611–1624, Aug. 2017.
[14] W. Deng and J. Yao, “Extended-state-observer-based adaptive control of electro-hydraulic servomechanisms without velocity measurement,” IEEE/ASME Trans. Mechatronics, early access, Dec. 12, 2020, doi: 10.1109/TMECH.2019.2959297.
[15] P. R. Raul, S. G. Manyam, P. R. Pagilla, and S. Darbha, “Output regulation of nonlinear systems with application to Roll-to-Roll manufacturing systems,” IEEE/ASME Trans. Mechatronics, vol. 20, no. 3, pp. 1089–1098, Jun. 2015.
[16] C. Wu, Y. Lin, and A. Eskandarian, “Cooperative adaptive cruise control with adaptive Kalman filter subject to temporary communication loss,” IEEE Access, vol. 7, pp. 93558–93568, 2019.
[17] W. Liu, Y. Liu, and R. Buknall, “A robust localization method for unmanned surface vehicle (USV) navigation using fuzzy adaptive Kalman filtering,” IEEE Access, vol. 7, pp. 46071–46083, 2019.
[18] L. Cheng, Z.-C. Zhu, G. Sheh, S. Wang, X. Li, and Y. Tang, “Real-time force tracking control of an electro-hydraulic system using a novel robust adaptive sliding mode controller,” IEEE Access, vol. 8, pp. 13315–13328, 2020.
[19] L. Wu, Q. Yan, and J. Cai, “Neural network-based adaptive learning control for robot manipulators with arbitrary initial errors,” IEEE Access, vol. 7, pp. 180194–180204, 2019.
[20] W. Gao, X. Wang, Q. Wu, and X. Yin, “Neural networks-based adaptive tracking control for a class of high-order stochastic nonlinear time-delay systems,” IEEE Access, vol. 7, pp. 63992–64004, 2019.
[21] N. R. Abjadi, J. Askari, J. Soltani, and G. R. Arab Markadeh, “Nonlinear sliding-mode control of a multi-motor Web-winding system without tension sensor,” IEEE Control Theory Appl., vol. 3, no. 4, pp. 419–427, Apr. 2009.

[22] P. R. Pagilla, N. B. Siraskar, and R. V. Dwivedula, “Decentralized control of Web processing lines,” IEEE Trans. Control Syst. Technol., vol. 15, no. 1, pp. 106–117, Jan. 2007.

[23] P. R. Pagilla, R. V. Dwivedula, and N. B. Siraskar, “A decentralized model reference adaptive controller for large-scale systems,” IEEE/ASME Trans. Mechatronics, vol. 12, no. 2, pp. 154–163, Apr. 2007.

[24] F. Claveau, P. Chevrel, and K. Knittel, “A 2DOF gain-scheduled controller design methodology for a multi-motor Web transport system,” Control Eng. Pract., vol. 16, no. 5, pp. 609–622, May 2008.

[25] D. Knittel, E. Laroche, D. Gigan, and H. Koc, “Tension control for winding systems with two-degrees-of-freedom H_{\infty} controllers,” IEEE Trans. Ind. Appl., vol. 39, no. 1, pp. 113–120, Jan./Feb. 2003.

[26] C.-L. Chen, K.-M. Chang, and C.-M. Chang, “Modeling and control of a Web-fed machine,” Appl. Math. Model., vol. 28, no. 10, pp. 863–876, Oct. 2004.

[27] D. E. Chang, J. Levine, J. Jo, and K.-H. Choi, “Control of Roll-to-Roll Web systems via differential flatness and dynamic feedback linearization,” IEEE Trans. Control Syst. Technol., vol. 21, no. 4, pp. 1309–1317, Jul. 2013.

[28] H. K. Khalil, Nonlinear Systems. Upper Saddle River, NJ, USA: Prentice-Hall, 2002.

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