Decentralized control for winding systems: Which incidence on reachable performances?

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***Abstract*—**Decentralized control strategy knows a renewed interest since the year 1990. This is due to the increasing performance of the computers and industrial networks allowing more complex controllers implementation and design but also to the progress made in optimization, through semidefinite programming and the LMI framework. This paper considers the problem of decentralized control as a special case of structured control design and focuses on the winding systems control problem. Several H_∞ controllers, from centralized to decentralized ones, will be evaluated and compared. Based on these results, the feasibility of a decentralized control scheme for winding systems will be discussed as well as the efficiency of the iterative LMI based algorithm used.

***Keywords*—Bilinear Matrix Inequalities, decentralized control, robust control, winding systems**

I. INTRODUCTION

Systems transporting paper, metal, polymers, or fabric are very common in the industry. Actual productivity constraints for winding systems such as web speed increase, web section decrease, and higher quality requirements call for control law offering both efficient performance and a high level of robustness. Furthermore, as for most of industrial processes, control laws of web transport systems have to be developed paying attention to maintainability. That is to say, as industrial winding plants are generally large-scale systems, a decentralized control law will be the only implementable solution on a practical point of view.

Owing to all these considerations, the following question can be raised: given the exacting performance and robustness requirements, but attainable by a centralized controller, what performance/robustness limitations are introduced by using a decentralized controller compared with a centralized one? We are interested here in analyzing the incidence of structure and order constraints on controllers on reachable performances. May be the results that will be obtained could give some insight on the feasibility of a decentralized control, or some indications to propose an alternative structure. That's the objective of this paper.

Until recently, most industrial web transport systems make use of decentralized PID controllers. Some researches on web handling control [1]-[3] propose PID, but also fuzzy or neural approaches. Multivariable control strategies have recently been proposed for industrial metal transport systems [4], [5], and paper transport systems [6], [7]. Interesting results have been also obtained on an experimental 3 motor platform (see fig. 1), with H_∞ multivariable robust controllers [8]-[10].

Decentralized control, after a first gain of interest during the years 70^{th} ([11], [12] and reference therein), because of industrial problematics, knows a renewed interest since the 90^{th}. It is possible to identify two reasons for that: the first one concerns the increasing performance of the computer and network communication allowing the effective and costless implementation of decentralized controllers. The second is related to the methodological and theoretical progresses made in optimization through the use of LMI and BMI [13]-[20]. Decentralized control belongs to the class of structured control problems as defined in [19]. This paper will address the problem of performance limitations in decentralized control by considering the case of winding systems. The quality of the controller (decentralized or not) will be measured through a H-infinity criterion. The degradation introduced by the structure or and order controller constraints will be analyzed.

The presentation of this paper is as follows; Description of the 3 motor bench is first presented in section II, as well as the control objectives. The working hypothesizes are specified to allow the comparison of the different controllers. Those controllers will be presented in section III, and designed by making use of the BMI framework to formalize the control problem and of advanced heuristics to solve the related optimization problem. Analysis and comparison of the controllers will be done in section IV. Based on it, some conclusions and perspectives will be presented in section V concerning the decentralized control problem of winding systems.

II. CONTROL OBJECTIVES FOR THE THREE MOTOR BENCHMARK WINDING SYSTEM

A. 3 motor bench

The considered system in this paper is an elastic web transport system including an unwinder, winder, and a traction motor (cf. figure 1). It therefore shows the inherent difficulties of web transport systems.

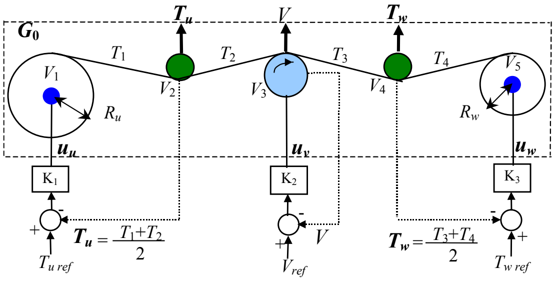

Fig. 1. Decentralized control scheme

Figure 1 shows the different variables used in the model: the control inputs $u=[\ u_u, u_v, u_w\ ]^T$ (the torque references of the three synchronous motors), and the outputs $y=[\ T_u, V, T_w\ ]^T$ (the unwinding web tension T_u, the linear velocity V, and the winding web tension T_w) of the system G_o (defined by the dashed box). The web velocity is measured near the master traction motor and the tensions are derived from force sensors measuring the web tension between rolls in the webline.

The detailed model of the web transport system considered here may be found in [10], [21]. It is derived from the following basic physical laws. The Hooke's law allows to model the web elasticity. The Coulomb's law describes contact between web and roll including friction. Finally, the mass conservation law enables the description of coupling between web velocity and web tension while the rotating speed dynamics are derived from the second fundamental relation of the mechanics.

Under the assumption made in [21], the whole model is built from the dynamical equations found for the tension of each part of the web and for the speed of each roll. For instance, the dynamic equations for T_1 and V_3 (cf. figure 1) are:

$$
\begin{aligned}
&L_1 \frac{dT_1}{dt} = V_2(ES + T_2) - V_1 \frac{(ES + T_2)^2}{ES + T_1}, \\
&\frac{d}{dt}\left(J_3 \frac{V_3}{R_3} \right) = K_3 U_3 + R_3 (T_2 - T_3) - f_3\left(\frac{V_3}{R_3} \right),
\end{aligned}
\tag{1}
$$

where E is the elastic modulus of the web, S its section, L_1 is the length between the two first rolls, R_3 is the radius of the third roll, J_3 is its inertia, K_3 is the torque per tension (volt) ratio of the motor and f_3 is the friction function depending on rotating speed; the non-linear model is deduced from the equations above; as our system is composed of $n_r = 5$ rolls, the order of the resulting model is then $2 \times n_r - 1 = 9$.

Remarks: Both unwinder and winder inertia J_i and R_i are time dependent and may vary substantially during the processing.

B. State space representation

The following state space representation of the nominal model will be used in the sequel to design the controllers. The numerical values (operating point, physical parameters adjusted from experimental data by identification) have been taken from [21].

$$
\begin{cases} E(t)\dot{X} = A(t)X + B(t)U \\ Y = CX \end{cases} \tag{2}
$$

where:

$$X^T = (V_1 \quad T_1 \quad V_2 \quad T_2 \quad V_3 \quad T_3 \quad V_4 \quad T_4 \quad V_5)$$

$$U^T = (u_u \quad u_v \quad u_w),\ Y^T = (T_u \quad V_3 \quad T_w)$$

The matrix $E(t)$, $A(t)$, $B(t)$, and C are detailed in the appendix.

C. Control requirements

The main concern is to prevent web breaks, folding, and damage which may slow down or and even stop the production line. Moreover, excessive or oscillating tension or velocity may cause the loss of the entire web (because of the deterioration). Therefore, transport control systems should meet the following requirements:

- Speed and tensions regulation with web tensions and speed decoupling so that a reference change on the speed does not affect the web tensions and conversely.
- Robustness with respect to variations in the web elasticity modulus due to temperature or moisture modification: these changes are very common on industrial process along the web line because of the several treatments applied to it at different places. Furthermore, the robustness is the condition to make the same control law working for different types of web.
- Robustness to variations in roll diameter: the same performance should be maintained throughout web processing.

Concerning this last point, a gain scheduling solution is not considered here but could be easily designed as a second step following e.g. [9], [21]. The choice has been made to consider the process behavior only around the nominal operating point.

D. Working assumptions

The control law efficiency (trade-off between performance and robustness) is supposed correctly evaluated by the H_∞ criterion proposed in [10] or [21]. Introduced initially to design one optimal centralized H_∞ controller (3 inputs, 3 outputs) this criterion will also be used for the design of decentralized solutions in order to make comparisons. The H_∞ criterion is built following the weighted mixed sensitivity approach ([22]-[24]).

Referring to figure 2, where $G_0(s)$ is the LTI model of the plant related to (2), the centralized controller $K(s)$ can be computed via γ-iteration thanks to the DGKF algorithm [24], in order to minimize the H_∞ norm of T_{zw}. By definition, T_{zw} is the closed-loop transfer function between the exogenous inputs w (reference signals T_{uref}, V_{ref}, T_{wref}) and the weighted outputs z. The weighting functions $W_p(s)$, $W_u(s)$, $W_t(s)$ constrain the frequency shaping of $S_e = (I + G_0 K)^{-1}$, the sensitivity function, $T_e = I - S_e$, the complementary sensitivity function, and KS_e, the input sensitivity function. They are defined by equation (3).

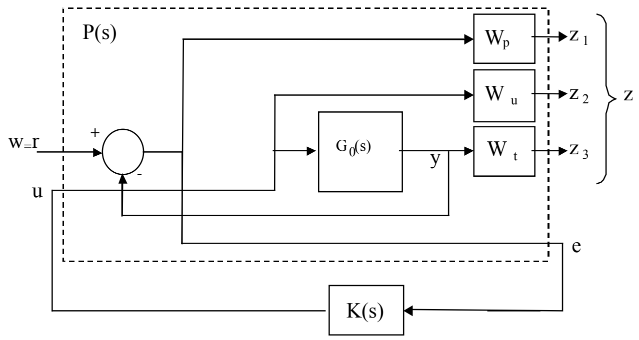

Fig. 2. Weighted model of the system

$$W_p = \begin{bmatrix} \frac{s/2+11}{s+0,01} & 0 & 0 \\ 0 & \frac{s/2+9}{s+0,01} & 0 \\ 0 & 0 & \frac{s/2+11}{s+0,01} \end{bmatrix}, \tag{3}$$

$$W_u = I_3,\ W_t = \begin{bmatrix} 2s & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & 2s \end{bmatrix}.$$

The next section will present the different types of (structured and order constraint) controllers that will be considered.

III. H$_\infty$ DECENTRALIZED CONTROLLER DESIGN

A. Controllers description, and design problem formulation

In the sequel, the decentralized structure shown on figure 1 will be assumed. The structured controller is composed of 3 elementary controllers associated respectively to the unwinder, the winder, and the traction motor. Additional constraints will be considered:

- Different order limitations on each elementary controller will be introduced, from 1 to 4.
- An explicit integral term, a PI or PID structure will be imposed or not, alternatively.

For each case, the same constraints are assumed to all the elementary controllers.

Finally, 6 structured decentralized controllers will be considered. They will be evaluated and compared in section IV (cf. tab. I):

- The first one, named "classical decentralized PI", had been tuned heuristically in [21], in order to optimize performances in the time-domain.
- The second one, named "H$_\infty$-decentralized PI" will be obtained here from the first one, by optimization in the BMI framework.
- The third one, the "H$_\infty$-decentralized PID" generalizes the second one by assuming a PID structure.
- The 4th, 5th and 6th are general (LTI) decentralized controllers. Their order is limited respectively to 6, 9 and 12 (assuming the same order for each elementary controller).
- The H$_\infty$ centralized controller will constitutes the reference. It is the 7th.

Some algorithms have been recently proposed in order to solve a certain class of BMI allowing among other to deal with the structured H$_\infty$ problem in the static output feedback case (see e.g. [13] to [20]). To synthesize the 6 decentralized controllers defined previously, the associated dynamical H$_\infty$ problems have first to be converted to static ones. This can easily be done thanks to the following results.

Let define for the sequel P(s) by the system matrix:

$$\left[\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & 0 \end{array}\right] \tag{4}$$

Let controller K(s) be defined by the system matrix of appropriate dimension:

$$\begin{bmatrix} A_K & B_K \\ C_K & D_K \end{bmatrix} \triangleq K_s \tag{5}$$

Theorem 1: [25]

Let us define the augmented model:

$$P_a(s) := \left[\begin{array}{cc|ccc} A & 0 & B_1 & 0 & B_2 \\ 0 & 0_{n_K} & 0 & I_{n_K} & 0 \\ \hline C_1 & 0 & D_{11} & 0 & D_{12} \\ C_2 & 0 & D_{21} & 0 & 0 \\ 0 & I_{n_K} & 0 & 0 & 0 \end{array}\right] \triangleq \left[\begin{array}{c|cc} A_a & B_{a1} & B_{a2} \\ \hline C_{a1} & D_{a11} & D_{a12} \\ C_{a2} & D_{a21} & 0 \end{array}\right] \tag{6}$$

Then the following equality holds.

$$F_l(P(s), K(s)) = F_l(P_a(s), K_s), \tag{7}$$

where $F_l(P,K)$ denotes a lower Linear Fractional Transformation (LFT) on P and K.

Proof: Obvious by construction.

Corollary:

The previous result obviously holds for the particular case considered here:

$$A_K = diag(A_{K_1}, A_{K_2}, A_{K_3}),\ B_K = diag(B_{K_1}, B_{K_2}, B_{K_3}),$$
$$C_K = diag(C_{K_1}, C_{K_2}, C_{K_3}),\ D_K = diag(D_{K_1}, D_{K_2}, D_{K_3}). \tag{8}$$

Theorem 2:

Let us consider P(s) as defined previously (4).

Let the controller K(s) be of the particular form:

$$K_{PI}(s)=\begin{bmatrix} k_{11}+k_{12}/s & 0 & 0 \\ 0 & k_{21}+k_{22}/s & 0 \\ 0 & 0 & k_{31}+k_{32}/s \end{bmatrix} \tag{9}$$

Let us construct the matrix gain $\overline{K}$ as:

$$\overline{K}\triangleq\begin{bmatrix} k_{12} & 0 & 0 & k_{11} & 0 & 0 \\ 0 & k_{22} & 0 & 0 & k_{21} & 0 \\ 0 & 0 & k_{32} & 0 & 0 & k_{31} \end{bmatrix} \tag{10}$$

Let us define the extended model $P_e(s)$ drawn in figure 3.

Then the following equality holds.

$$F_l\left(P(s),K_{PI}(s)\right)=F_l\left(P_e(s),\overline{K}\right) \tag{11}$$

Proof: Obvious by construction.

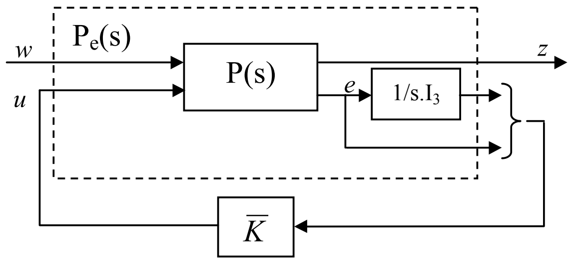

Fig. 3. Output extension principle scheme

We end up to a static output feedback gain presenting indeed a different structure according to the employed reformulation methodology, but which permit us to formulate a single static output feedback H∞ optimization problem under structural constraints.

Theorem 3:

Let $\widetilde{P}$ be P_a or P_e, and $\widetilde{K}$ be K_s or $\overline{K}$, depending on the case considered.

$$\widetilde{P}(s)=\left[\begin{array}{c:cc} \widetilde{A} & \widetilde{B}_1 & \widetilde{B}_2 \\ \hdashline \widetilde{C}_1 & \widetilde{D}_{11} & \widetilde{D}_{12} \\ \widetilde{C}_2 & \widetilde{D}_{21} & 0 \end{array}\right] \tag{12}$$

Consider

$$M(X,\widetilde{K})=\begin{bmatrix} \widetilde{A}^T X+X\widetilde{A} & X\widetilde{B}_1 & \widetilde{C}_1^T \\ \widetilde{B}_1^T X & -\gamma I & \widetilde{D}_{11}^T \\ \widetilde{C}_1 & \widetilde{D}_{11} & -\gamma I \end{bmatrix} + \begin{bmatrix} X\widetilde{B}_2 \\ 0 \\ \widetilde{D}_{12} \end{bmatrix}\widetilde{K}\begin{bmatrix} \widetilde{C}_2 & \widetilde{D}_{21} & 0 \end{bmatrix} + \left\{\begin{bmatrix} X\widetilde{B}_2 \\ 0 \\ \widetilde{D}_{12} \end{bmatrix}\widetilde{K}\begin{bmatrix} \widetilde{C}_2 & \widetilde{D}_{21} & 0 \end{bmatrix}\right\}^T \tag{13}$$

Finding $X>0$ such that

$$M\left(X,\widetilde{K}\right)<0 \tag{14}$$

is a BMI feasibility problem in X and $\widetilde{K}$ ensuring:

- *The internal stability of $F_l(\widetilde{P},\widetilde{K})$ and,*
- $\left\|F_l\left(\widetilde{P},\widetilde{K}\right)\right\|_\infty<\gamma$.

Proof:

See Gahinet and Apkarian [26]. See also [20] in the decentralized case.

Because of the structural constraints on the static output feedback $\widetilde{K}$, equation (14) cannot be reduced (as it is usually done for the classical H∞ problem) to a convex optimization problem under LMI constraints. However, some algorithms can deal with such BMI problems: see for instance [13]-[20]. After some experiments, we decided to use alternatively the two methods proposed in [18] and [19] to compute the different structured H∞ controllers (these algorithms having a satisfactory convergence velocity). It leads to an Iterative LMI (ILMI) algorithm.

IV. Results

Our objective is to study the incidence of structural controller constraints on reachable performances. To evaluate and compare the different controllers, the global H∞ criterion $\left\|T_{zw}\right\|_\infty$ is used.

Tab. I. Evaluation of the structured controllers

Controllers	$\left\|T_{zw}\right\|_\infty$	$\left\|S_e\right\|_\infty$	$\left\|KS_e\right\|_\infty$	$\left\|T_e\right\|_\infty$
Classical decentralized PI	653,64	26,97	5,65	26,88
H∞-decentralized PI	54,38	4,24	2,72	3,84
H∞-decentralized PID	37.23	3.72	2.36	4.13
6th order struct. controller	30.43	4.01	2.27	4.95
9th order struct. controller	26.71	3.13	2.45	4.25
12th order struct. controller	25.00	2.71	2.47	3.92
H∞-centralized controller	**4,92**	**1,86**	**3,62**	**1,73**

It is completed by the H_∞ norm of the sensitivity function S_e, T_e, and KS_e to give more insight on the robustness properties, and by some simulations in the time-domain. The scenario of simulation is chosen in order to appreciate the decoupling properties of the controller. Different values of the web elasticity modulus are considered to complete the robustness analysis. The results are summed up in table I. The simulation results are given in figure 4 and 5.

Let us first consider the decentralized PI. The "classical" ones (proposed in [21]) are efficient if one consider the response time to references step changes. However, the decoupling is not good. More importantly, the associated $\|T_{zw}\|_\infty$ criterion is very high and the robustness properties are so bad that this solution is not a practical one (simulations with an elastic modulus variation confirm this). With the same structure, the H_∞-decentralized PI computed thanks to the ILMI algorithm presented in section III leads to a much lower H_∞ criterion (criterion divided by 12). However, the H_∞ criterion remains far away from the optimal one (achieved by the centralized H_∞ controller). Introducing a derivative term as an additional degree of freedom improves the results but not as important as desired. If robustness and decoupling of the initial decentralized PI controllers are improved, the response time to references step changes is deteriorated.

Relaxing the PI/PID structure constraint on each elementary controller leads to slightly better results. The H_∞ criterion decreases as the order of the controller increases. It can be noticed however that the H_∞ criterion decreasing becomes slower and slower and will converge to a value still far from the optimum (by a ratio of 5). Moreover, the time domain simulation (figure 5) shows an oscillating behavior that may not be acceptable.

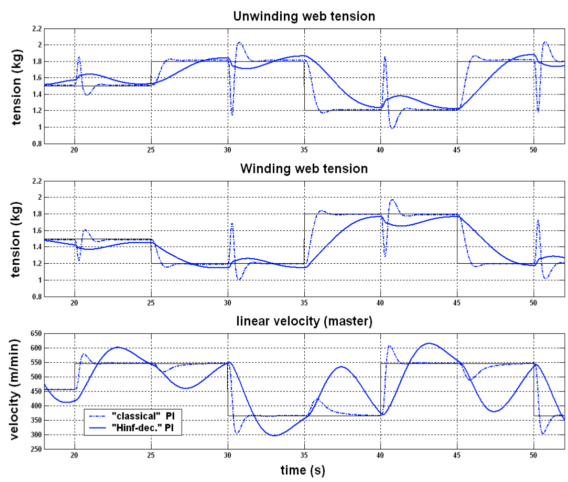

Fig. 4. Classical and H_∞-decentralized PI comparison

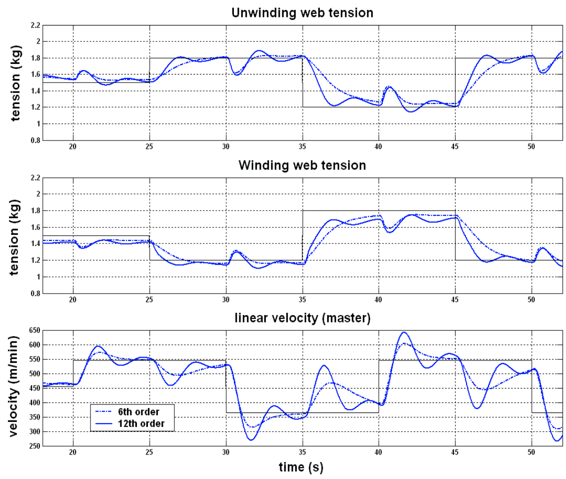

Fig. 5. 6th and 12th order struct. controllers comparison

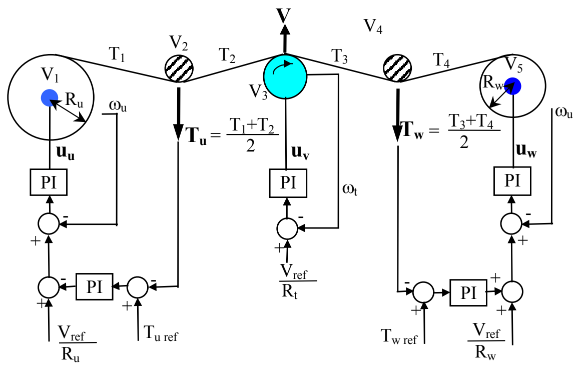

Fig. 6. Industrial control scheme

V. CONCLUSION AND PERSPECTIVES

The results of the paper call for some comments. At first, the efficiency of recently proposed iterative LMI algorithms has been shown for the problem considered. The gain of robustness and performance appeared clearly as the structure or order constraints on the controllers were relaxed. At second, a gap between the H_∞ criterion obtained with the optimal centralized controller on one side and the three tracks decentralized controllers on the other side has been observed. This seems to illustrate that the performance limitations come from the structure constraints considered.

The perspectives of this work are the following. First, it will be interesting to propose and analyze other structures. The choice of the H_∞ criterion may also be questioned in the sense: does it really give a relative measure of the quality of the controller as the criterion value becomes high? At second, the interest of overlapping [27], [28] could be analyzed. The pertinence of the more classical industrial control scheme (see figure 6 and [10]) commonly used for the winding systems could be investigated. In this case, the web transport velocity is regulated with a local PI controller for the traction motor and the two other motors (associated with the winder and the unwinder) are regulated by the way of two local cascade controllers. Such a structure is richer than the one considered in this paper in the sense that more information (tension and velocity) is accessible to the winder and unwinder controllers. Optimizing it seems both challenging and promising. At third, it will be interesting to extrapolate the conclusion obtained with this three motors high velocity winding system benchmark to bigger one for which a sequential design will be essential.

APPENDIX

$$\begin{cases} E(t)\dot{X} = A(t)X + B(t)U \\ Y = CX \end{cases}$$

where:

$$X^T = \begin{pmatrix} V_1 & T_1 & V_2 & T_2 & V_3 & T_3 & V_4 & T_4 & V_5 \end{pmatrix}$$

$$U^T = \begin{pmatrix} u_u & u_v & u_w \end{pmatrix},\ Y^T = \begin{pmatrix} T_u & V_3 & T_w \end{pmatrix}$$

$$E(t) = diag\left(J_u(t), L_1, J_2, L_2, J_t, L_3, J_4, L_4, J_w(t)\right)$$

$$A(t) = \begin{bmatrix} -f_1(t) & R_u(t)^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -E_0 & -V_0 & E_0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -R_2^2 & -f_2 & R_2^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & V_0 & -E_0 & -V_0 & E_0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -R_t^2 & -f_3 & R_t^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & V_0 & -E_0 & -V_0 & E_0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -R_4^2 & -f_4 & R_4^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & V_0 & -E_0 & -V_0 & E_0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -R_w(t)^2 & -f_5(t) \end{bmatrix}$$

$$B^T(t) = \begin{bmatrix} -K_uR_u(t) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & K_tR_t & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_wR_w(t) \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 1/2 & 0 & 1/2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/2 & 0 & 1/2 & 0 \end{bmatrix}$$

V_i, R_i, J_i, and f_i are the linear velocity, the radius, the inertia and the viscous friction coefficient of the roll *i* respectively. T_i and L_i are the web tension and the web length between the roll *i* and the roll *i+1*. K_u, K_t, K_w are the torque constants of each motor. V_o is the nominal linear web velocity. E_o is a parameter depending on elasticity modulus *E*, on web section *S*, and on nominal tension T_o: $E_o = ES + T_o$. All parameters varying during the winding process are expressed as functions of time.

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