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Performance of a web transport system with tension control subsystem using speed as control input

Nicola Ivan Giannoccaro
Dep. of Innovation Engineering, University of Salento
Lecce, Italy
ivan.giannoccaro@unisalento.it

Issei Uchitomi Tetsuzo Sakamoto
Dep. of Control Engineering
Kyushu Institute of Technology
Kitakyushu, Japan

Abstract—**In this paper, the authors improve the control performance of a multi-span web transport system by introducing a new decentralized control strategy using the overlapping decomposition. The system is composed of eleven guide rollers, four main sections mutually interconnected with each other. The overlapping decomposition requires a derivative action on the controlled variables. All the theoretical aspects will be shown together with the preliminary experimental results demonstrating the improvements of the proposed approach.**

*Keywords— **Web transport system, Large scale systems, Decentralized control, Overlapping decomposition***

I. INTRODUCTION

The industrial web handling systems are usually composed of a large number of rolls and categorized as a large-scale system that is decomposed in subsystems for web tension control and web speed control; until now, most industrial web transport systems use decentralized PID controllers. However, all those subsystems have strong interactions with each other and the control of each subsystem is heavily influenced by the interactions with the neighboring subsystems. In the large-scale systems [1] the control decentralization is necessary because the systems to be controlled are too large and the problems to be solved are too complex. A good solution to the necessity of the decomposition was introduced since 1998 [2-3] with a methodology based on a decomposition of the system into subsystems overlapped to take into account the mutual effects of the neighbouring subsystems. The simulation results [2-3] and some recent experimental tests [4-5] demonstrated that the controller design became easy and that the control performances were better than the conventional decentralized controllers based on a disjoint decomposition.

This work is aimed to illustrate and to discuss the applicability of a variant of the overlapping decomposition for improving the decentralized control. The variant, which will be fully explained in the paper, is related to a different use of the inner motor control loop that can be changed to the ‘speed control mode’ for all the servomotors. Moreover a novel control strategy that consider as control variables, the velocities for the inner systems sections and the tensions for the unwinder and winder sections will be introduced and explained. The main consequence of this control strategy is related to the possibility of avoiding the time-consuming evaluation of the radius changes, necessary for different control strategies [4], that becomes inapplicable with the hardware and the sampling time used in this work. Moreover, the overlapping decomposition applied to the proposed control strategy requires a derivative action on the controlled variable that improves the control performances. A linear model of the system is considered in order to formulate the overlapping decomposition control in the proposed setting.

Some experimental tests carried out by using an experimental multi-span web transport system, specially designed and realized for creating a situation similar to a large-scale system with several sections (four main sections) mutually interconnected to each other, will complete the analysis.

II. DESCRIPTION OF THE REALIZED WEB HANDLING SYSTEM

The realized system, already introduced in [4,6,7,8], is composed by four main sections strongly interlaced each other and 12 rollers that constitute the system. It has been furtherly improved with the substitution of some hardware. The system (depicted in the photos in Fig.1 and in Fig.2 and in the scheme in Fig.3) is composed of twelve rolls placed on a mechanical frame at different heights, realized in order to represent a large transport system similar to many industrial ones. The movements of the web on the twelve rolls is guaranteed by 4 servomotors (Fig.2) named Motor 1, 2, 3 and 4; Motor 1 and 4 are referred to the unwinder and winder roll respectively (Fig.2). Two couples of tension sensors, (one for each side of the web), are placed on the device. The first couple of tension sensors is placed right after the unwinder roll, the second one right before the winder roll. The first couple of tensions sensors is followed by the Motor 2 that precedes a couple of guide rolls where the web is wrapped to maximize the contact area between the web and the drive roll. The Motor 3 is connected to the second couple of tension sensors that precedes the winder roll. All the servomotors are set in velocity mode control so that every control input is given as the motor speed. The control input signals u_i, i=1….4 are sent to the servomotors by using a 4 channel D/A board. The tension sensors signals feed a 4 channel A/D board, and the average tension value of the two corresponding sides is considered for measuring the tension after the unwinder roll (named T_1 in Fig. 3) and before the winder roll (named T_4). The 4 motor encoder signals (including the speed signals of unwinder section and lead section) feed a digital counter.

The controller's CPU receives signals through A/D boards and counters, performs the control algorithm (C language and Linux operating system), and outputs the command signals in real time to the motor driver through D/A boards.

The whole system is accurately mounted on a mechanical frame, designed for supporting the components of the system, and each of the 4 motors is connected to the respective roller using connection joints. The power cables were placed far away with respect to the signal cables (Fig.1), and all the cables were covered with insulating tape. Important hardware changes have been recently realized for improving the system shown in [4]. The most important change is related to the substitution the Motors 2 and 3 that in [4] were smaller (100W, 0.318Nm maximum torque), with more powerful motor with the same characteristics of Motor 1 and 4 (750W, 2.39Nm) to tackle the friction forces. Moreover, a filtering group (Fig.1) has been inserted to the analog feedback signal of the tension sensors.

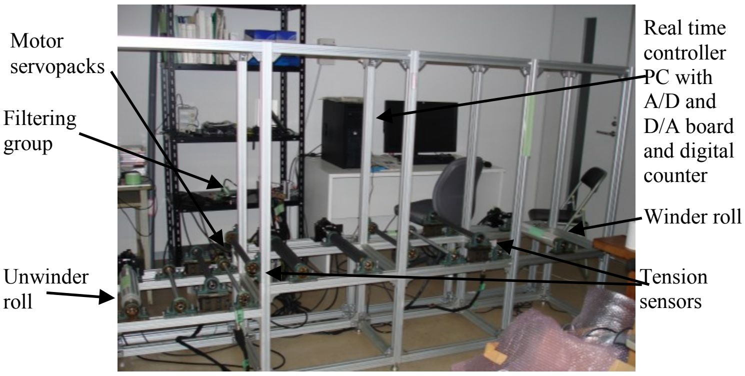

Fig. 1. Photo of the actual web transport system platform

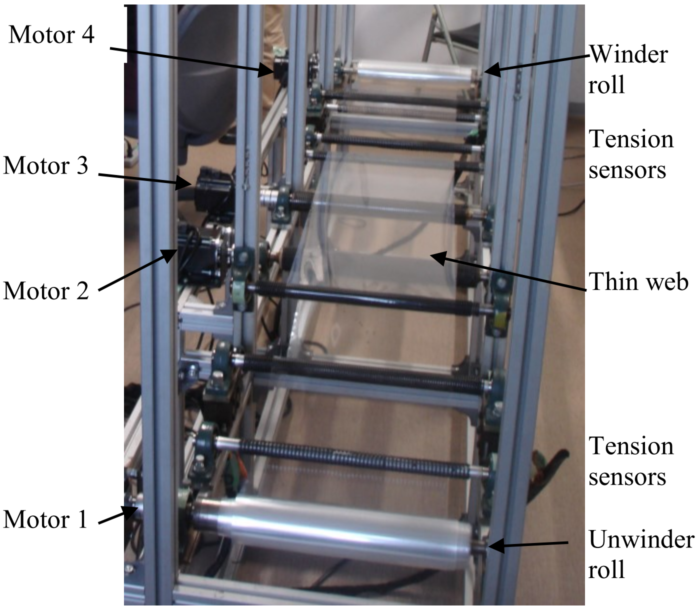

Fig. 2. Servomotors position on the platform

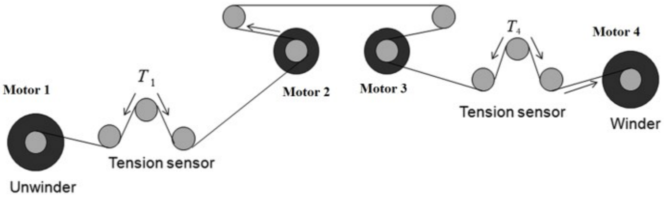

Fig. 3. Scheme of the actual web transport system platform

III. MODELLING AND CONTROL

A. System parameters and modelling

The system is constituted by 4 drive rolls that divide it in three sections; section 1(span L_1 from Motor 1 to Motor 2), section 2 (span L_2 from Motor 2 to Motor 3) and section 3 (span L_3 from Motor 3 to Motor 4).

Our mathematical model of the web transport systems is based on the relations expressed by the following three equations (see details in [6],[9], [10]) applied at each section between two consecutive drive rolls. Assuming the Voigt model for the web dynamics, the model expressions in the Laplace domain are described by Eq. (1-3):

$$\varepsilon(s) = \frac{1}{L \cdot s} \cdot [V_b(s) - V_a(s)] \tag{1}$$

$$s \cdot J_k(s) \cdot \omega_k(s) = r_k \cdot [F_{k+1}(s) - F_k(s)] + U_k(s) - C_k - K_{fk} \cdot \omega_k(s) \tag{2}$$

$$F(s) = A \cdot \eta \cdot [\frac{1 + T_v \cdot s}{T_v \cdot s}] \cdot s \cdot \varepsilon(s) \tag{3}$$

where (1) expresses the law of conservation of mass for each web section for evaluating the relation between the speeds (named V_a and V_b) of two adjacent drive rolls and the strain ε in the web, L is the length of the section span (considered constant between two drive rolls). Eq. (2) is a torque balance equation of the tension forces F_{k+1} and F_k applied to the sides of the k^{th} drive roll having radius r_k, inertia J_k and angular velocity ω_k. U_k is the motor torque applied to the k^{th} roll, C_k is the dry friction torque, and K_{fk} is the viscous friction coefficient. Eq. (3) expresses the linear viscoelasticity of the web-material, where F is the force applied to the web, A is cross sectional area of the web, η is the viscosity modulus, $T_v = \eta / E$, with E the elastic modulus.

B. Control strategy

Important modifications have been realized on the control strategy [4]; the first important modification is referred to the observation that the unwinder and winder roll radiuses change noticeably during the web transport and this phenomenon becomes very important with the increase of the web speed. It is true that it could be possible to take into account the change of the radius value, evaluating the radius variation by the knowledge of the roll angular speed and of the web thickness; but this evaluation produce a delay on the real time control system that could influence negatively the system performance. For this reason, differently from the past, the control strategy, here proposed, has been organized in the following way. The velocity control is referred to the velocities (variables V_2 and V_3) of the internal rolls driven by the Motors 2 and 3 that do not change their radius. For the unwinder and winder drive roll, the control is referred to the tension forces (variables T_1 and T_4) measured by the force sensors (Fig.3).

Considering (1) and (3), (4) and (5) express the relation between the control variables in the Laplace domain:

$$T_1(s)=\frac{P(s)}{L_1}\cdot[V_2(s)-V_1(s)] \tag{4}$$

$$T_4(s)=\frac{P(s)}{L_3}\cdot[V_4(s)-V_3(s)] \tag{5}$$

where $P(s)= A\cdot\eta\cdot[\frac{1+T_v\cdot s}{T_v\cdot s}]$.

A global scheme of the system, considering the proposed control variables for each drive rolls, is shown in Fig.4; in the diagram, an overlapped decomposition [3,4] of the entire system is also indicated (dotted line rectangles) that introduces the subsystems 1,2,3 and 4. In this case, due to the control strategy proposed, the control input variables are different. The control inputs of subsystems 1 and 4 are torque (indicated as U_1(s) and U_4(s) in Fig. 4), while the control inputs of subsystems 2 and 3 are angular speed (U_2(s) and U_3(s) in Fig. 4).

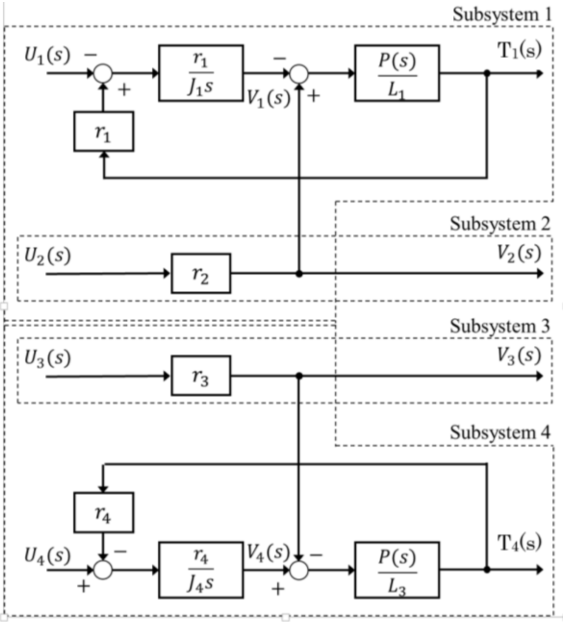

Fig. 4. System model scheme with overlapping decomposition subsystems

C. Analysis of the overlapping decomposition effects and control strategy

The advantages of the overlapping decomposition are well known [3]; since 1998 it was demonstrated [3] that a decentralized controller based on overlapping decomposition permits considering some mutual interactions between subsystems. The resultant control system has better control performance compared with a decentralized control system based on disjoint decomposition, and besides it makes the controller design simpler. Following this approach, the realized web handling system (Fig 5a) has been divided in 4 overlapped sections (Fig.4b), and the new control inputs $(\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4)$ (Fig 4c) are calculated through a conversion N^{-1}.

The overlapping decomposition relations are expressed in (6)-(9) for the subsystems indicated in Fig. 4.

$$T_1(s)=\frac{\frac{P(s)}{L_1}}{s+\frac{P(s)\cdot r_1^2}{L_1\cdot J_1}}\cdot[\frac{r_1}{J_1}\cdot U_1(s)+(r_2\cdot s\cdot U_2(s)] \tag{6}$$

$$\begin{aligned}V_2(s)&=r_2\cdot U_2(s)\\ V_3(s)&=r_3\cdot U_3(s)\end{aligned} \tag{7}$$

$$T_4(s)=\frac{\frac{P(s)}{L_3}}{s+\frac{P(s)\cdot r_4^2}{L_3\cdot J_4\cdot s}}\cdot[\frac{r_4}{J_4}\cdot U_4(s)-(r_3\cdot s\cdot U_3(s)] \tag{8}$$

$$N^{-1}=\begin{bmatrix}\frac{r_1}{J_1} & r_2\cdot s & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & -r_3\cdot s & \frac{r_4}{J_4}\end{bmatrix} \tag{9}$$

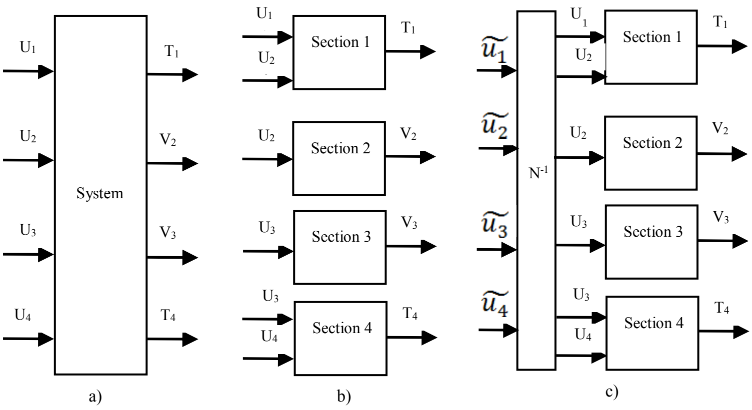

Fig. 5. Schematic details of the overlapping decomposition process

Finally the control input vector $U=[U_1(s)\quad U_2(s)\quad U_3(s)\quad U_4(s)]$ is calculated from the virtual control input vector of the overlapped decomposition system $\tilde{U}=[\tilde{U}_1(s)\quad \tilde{U}_2(s)\quad \tilde{U}_3(s)\quad \tilde{U}_4(s)]$ by (10)

$$U=N\cdot\tilde{U} \tag{10}$$

where from (9) N is given by (11).

$$N = \begin{bmatrix} \frac{r_1}{J_1} & r_2 \cdot s & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -r_3 \cdot s & \frac{r_4}{J_4} \end{bmatrix} \qquad (11)$$

Observing Eq. (10) and (11), it is very interesting to note a derivative effect, due to the factor '*s*' in the first and fourth row of the transformation matrix N^{-1} that never appeared in previous applications [3,4] of the overlapping decomposition. This effect, due to the choice of the subsystems and of the control input for each section, could heavily modify the control performance; for this reason, the analysis of the proposed approach and an evaluation of the benefits may be an important objective of the present research.

Each of the four overlapped subsystems is controlled with simple PI controllers, that generate the virtual control input vector $\tilde{U} = [\tilde{U}_1(s) \ \ \tilde{U}_2(s) \ \ \tilde{U}_3(s) \ \ \tilde{U}_4(s)]$ for driving the servomotors and controlling the control variable vector [T_1, V_2, V_3, T_4], obtained by the couple of tension sensors (tensions T_1 and T_4) and by the encoders of the motors 2 and 3 (velocity V_2 and V_3) .

The use of PI controllers is the most widely used and popular for this kind of systems (i.e. in [4], [5], [8], [11]) and it is also considered a reference when different and more complex controllers are used (i.e. in [12], [13]).

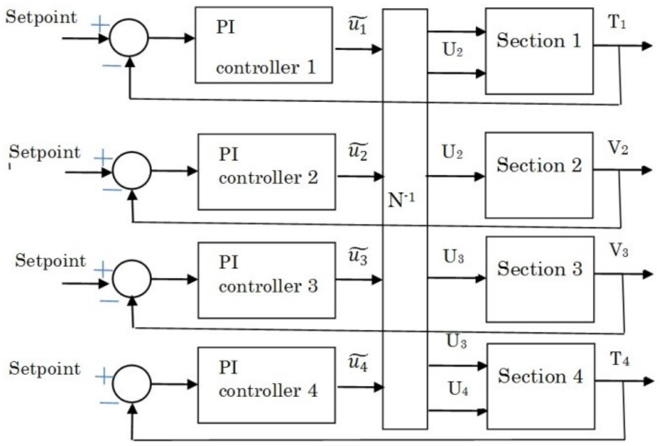

Fig. 6. Schematic details of the overlapping decomposition process

D. Estimation of geometrical and parameters

The development of the control strategy requested a preliminary step of simulation; for realizing a suitable model of the system, the geometrical data reported in Table I have been adopted and measured on the system. In addition a value of the cross-sectional area *A* equal to 1.2 10^{-5} m^2, of the viscosity modulus μ=1.5 10^9 [Ns/m^3], elastic modulus *E*=9.8 10^9 N/m^2. The evaluation of the inertia of the drive rolls has been carried out with experimental tests on the single rolls and by estimating the corresponding relation between the applied torque and the corresponding angular acceleration.

The inertia values indicated in Table I for the four servomotors are slightly different though the motors are of the same type and model, but this is reasonable considering the different weights of the corresponding rolls and also the different individual characteristics.

TABLE I.

	Geometrical data of the platform			
	Section 1	***Section 2***	***Section 3***	***Section 4***
Drive rolls radius r_i [m]	0.039	0.0286	0.0271	0.035
Drive rolls inertia J_i [kgm^2]	0.0025	0.002	0.003	0.0018
Length L_i [m]	0.83	1.28	1.20	-

IV. SIMULATION RESULTS

The effectiveness of the proposed overlapping decomposition strategy has been firstly tested by carrying out several simulations all referred to a starting position where all the system is at rest. This is the most difficult condition that could lead to high and dangerous tension forces during the transient period for achieving the desired speed.

Accordingly, the control strategy has been tested on a setpoint profile that achieves firstly the transport tensions T_1 and T_4 at the unwinder and winder section respectively, and then, a smooth increase of the speed setpoint V_2 and V_3. A comparison between the system performance with or without the proposed overlapping decomposition is shown in Figs 7 and 8.

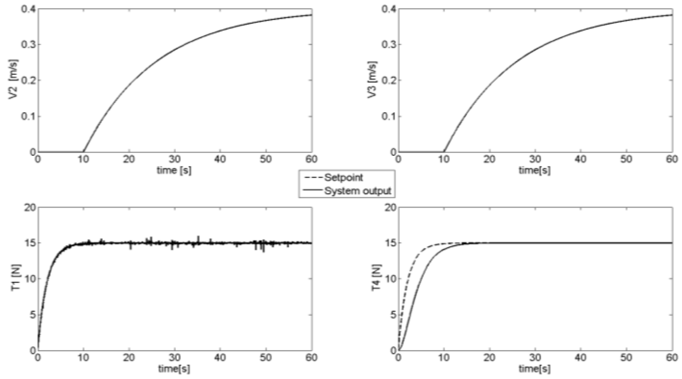

Fig. 7. Simulation results without overlapping decomposition

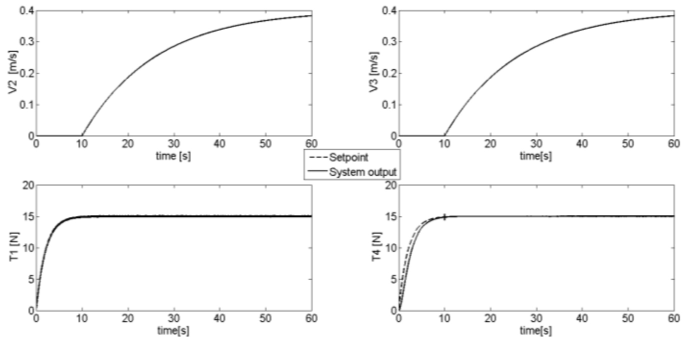

Fig. 8. Simulation results with overlapping decomposition

It is evident that the proposed strategy permits better performances of the control strategy: considering the tension forces T_1 and T_4 it is evident that the overlapping decomposition ensure a quicker achievements of the setpoint requirements. This is probably due to the derivative effect included in the proposed overlapping decomposition as it is evident in the expression of matrix N (11). The velocities control results are very good in both the cases, and there is a perfect behavior with respect to the chosen setpoint. Moreover, because the rolls driven by the motors 2 and 3 does not change their radius during the web transport, it is not necessary to include in the firmware a radius variation calculation that could provoke not predictable delays during the on-line control, as it happened with the previous control strategies choices [4].

Other simulation were also carried out assuming some noise on the feedback signals, and in any case, the possibility of using the proposed overlapping decomposition, improves the performance of the control system on the controlled variables of velocities and forces.

V. EXPERIMENTAL RESULTS

In order to test experimentally the proposed control strategy, preliminary experimental tests have been carried out on the platform with the objective of refining the PI controller parameters K_P and T_I starting from the values obtained in the simulations. Finally, for the particular shape analyzed starting from the motionless condition, for each controller two cases of PI controller parameters have been considered. The first value is referred to the phase where the control system is mainly dedicated to achieve the transport system tensions T_1 and T_4 (the first period of 10 seconds, the second period for the remaining period). The PI parameters used in the tests are shown in Table II.

TABLE II.

	PI controller parameters used in the experiments			
	Controller 1	***Controller 2***	***Controller 3***	***Controller 4***
K_p (first period)	0.5	0.05	1.5	0.3
K_p (remaining period)	0.5	0.05	1.5	0.3
T_I (first period)	0.006	0.0015	0.015	0.006
T_I (remaining period)	0.001	0.0015	0.015	0.001

In Figs. 9-12, the results of 4 experimental tests are shown, which are named as the tests 1,2,3 and 4. For each test, in the upper part of the Fig., the behavior of the tension forces T_1 and T_4 in comparison with their setpoint is shown; in the lower part, the behavior of the controlled velocities V_2 and V_3 is depicted. The tests are referred to different setpoint values of the velocities of the web transport and of the tension forces and also to different profiles of the setpoint for achieving the final value starting from a motionless position.

It is necessary to underline that, for the physical continuity of the system, the setpoint has the same value for the couples of the controlled variables T_1 and T_4 and for the controlled variables V_2 and V_3.

All the experimental tests depicted in Figs. 9-12 clearly show a very good performance of the proposed control strategy with respect to all the four controlled variables and an excellent capacity of achieving the desired velocity and tension force without dangerous peaks of force on the web.

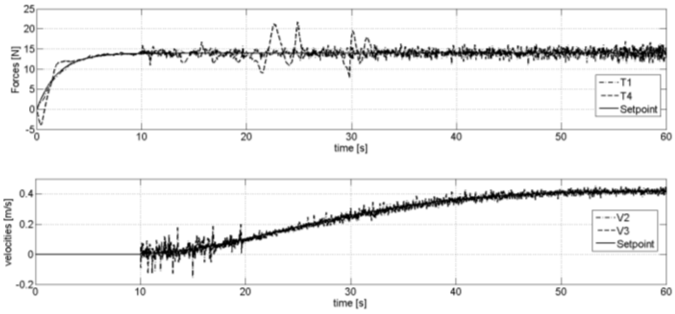

Fig. 9. Experimental results: test 1

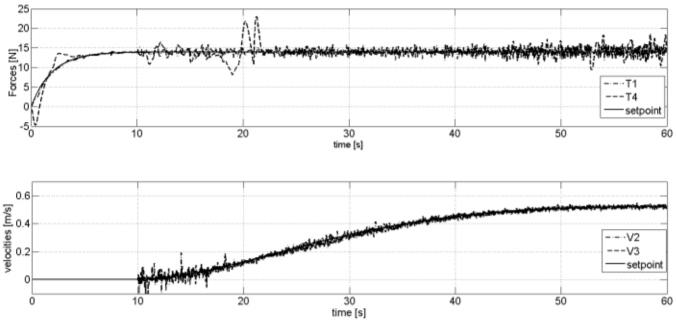

Fig. 10. Experimental results: test 2

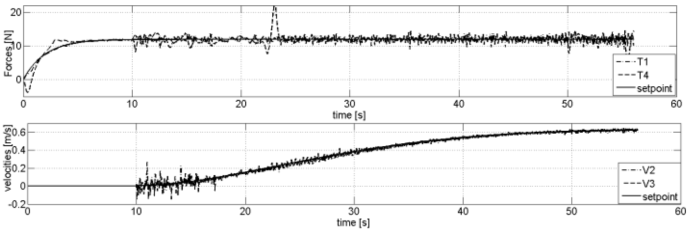

Fig. 11. Experimental results: test 3

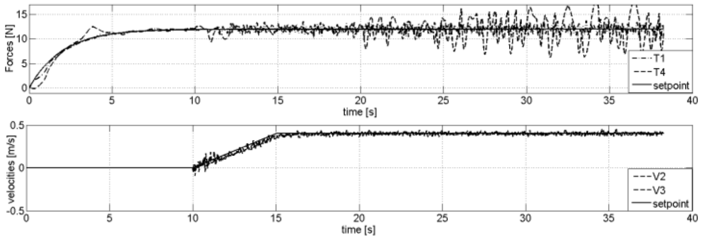

Fig. 12. Experimental results: test 4

The results of the experimental tests here proposed and of many other tests carried out confirm the applicability and robustness of the proposed strategy. The control performances show improvements or at least similar behaviour of the results obtained with PI controllers ([4], [5], [11]) or with more complex controllers ([8], [12], [13]).

VI. CONCLUSIONS

The importance of testing innovative control strategies for improving the performance of web handling systems in such a way to guarantee tracking properties and perturbation rejection of web speed and tension is well known in this field, and it is probably of great interest for the industries to successfully run these kind of systems as well.

This paper shows the results of a research that tried to improve the performance of a web handling system, which can be regarded as a large-scale system. The system presented in ref [4,8], has been furtherly improved with some substantial hardware modification presented in this paper.

Moreover, an innovative control strategy based on a novel overlapping decomposition and simple PI controllers is here introduced. The simulation results and the experimental tests demonstrate the applicability and the advantage of the proposed approach also combining a strategy with an opportune division of the startup of the force and velocity variables from the motionless state. The proposed technique of using the speed signal as control input may be very useful for the control performance.

Further researches will be focused on other experiments with more severe dynamic condition. The presented results may show that the proposed strategy could be applied also to the requirements such as very high web velocities or brusque requested setpoint changes.

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