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Design, Analysis and Validation of an Observer-based Delay Compensation Structure for a Network Control System

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Abstract— **A pressing issue of Network Control Systems is the time-varying delay which alters the system's performance. The current study designs and analysis a control structure based on a communication disturbance observer for delay compensation for second order linear processes. The proposed networked control system is tested through simulations and experiments, using a new network model recently proposed by the authors, for a scenario involving random delay variation and packets loss during network transmissions.**

I. Introduction

Low cost, high fault tolerance and reliability of today's networks opened a new perspective in the field of control structure design: the network control system (NCS). A NCS is a feedback control system where information between the components of the control loop is transferred using real-time networks ([1]). The main advantages of NCSs are reduced costs and wiring, broad action area, modularity, high reliability and flexibility, robustness to failure, ease of re-configurability and maintenance ([1], [2]).

Besides a lot of advantages, a NCS has also shortcomings, induced by the network component, like time varying delays, data loss and bandwidth limitations that affect system's performance and stability ([1], [2], [3]). For addressing the particular issues of NCSs, several control strategies were proposed in the literature, like the Smith predictor ([4]), predictive control ([5]), gain scheduling ([6]), stochastic optimal control ([7]) or event based control ([8]).

A new method for delay compensation in NCSs, inspired from classical control theory ([9]), considers the delay as additive disturbance acting at the input of the process ([10]). This disturbance is estimated through a communication disturbance observer (CDOB), whose output is used to reject its effect from the controller's point of view. While most of the methods mentioned require a model for the time delay, or impose some kind of delay estimation/measurement, the usage of the CDOB based method has the main advantage that no information about the time delay instantaneous values or time delay variation rate is needed - the time delay is treated as an unknown input disturbance. Moreover, the CDOB method avoids any synchronization issues that would appear in delay measurements over the network ([11]).

In order to highlight the main contributions of the paper, first, the following remark has to be specified. The study from [10] is limited to first order processes. However, in control design practice, many second order benchmark process models can be encountered. In this context, the current paper extends the design of the CDOB method for second order processes. Furthermore, an elaborate analysis is made concerning the disturbance estimation and rejection, which implies: setting the optimum gains for the observer in correlation with certain cut-off frequencies, comparing different types of observers (full order and reduced order). Finally, the peaking phenomenon of the observer is discussed as an implementation issue, and the overall control structure is tested in a realistic scenario including time-varying delay and packet loss.

The CDOB method was validated through simulations and experiments, which are in concordance. For the experiments a network emulator was considered, which realistically characterizes wide area network transmissions.

The remainder of this paper is organized as follows. Section II presents the design for the CDOB method, and the analysis need for adjusting the design parameters. In Section III, the best CDOB version integrated into the overall control structure is tested through simulations and experiments. Section IV states the final conclusions and future work.

II. Network Control Structure with CDOB

A. Design of the Network Control Structure

The aim of the current study is to design a network control structure that will reject the disturbance effect of the network and the local disturbances, while also ensuring satisfactory process control performances.

The proposed network control structure is presented in Fig. 1. The process is situated remotely, being separated from the controller through a network, which is considered as a discrete time nonlinear system. At the process level, the local disturbance d is compensated by a local feedback loop composed out of a disturbance observer (DOB) and a disturbance compensator (DCO). At the controller level, a CDOB and a conventional controller are used. The CDOB compensates the effect of the delay disturbance from the controller's point of view, i.e., due to the CDOB, the controller "looks at the process" as if it is unaffected by communication disturbances.

As a working design hypothesis, the network system is idealized as a time varying delay element. By considering that the plant is linear, the network delays on the feedback path and direct path from Fig. 1 can be merged, obtaining a round-time-trip (RTT) delay τ at the input of the process. The RTT is considered as a delay disturbance d_n, defined as

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the difference between the transmitted control signal u_r and the received control signal u_n ([10]):

$$d_n(t) = u_n(t) - u_r(t) \tag{1}$$

with

$$u_n(t) = u_r(t-\tau) \tag{2}$$

In this context, the Network model from Fig. 1 is reduced to a unitary direct path with an additive delay disturbance ($u_n(t)=u_r(t)+d_n(t)$) and a unitary feedback path ($y_n=y_p$).

The network control structure design is based on the following strategy:

-- a local feedback loop is designed (DOB+DCO) for rejection of the local disturbance.

-- a conventional controller is designed for local control of the plant (the network will be further introduced between the controller and the plant).

-- a CDOB is designed which, coupled with a model of the process, rejects the delay disturbance, from the controller's point of view.

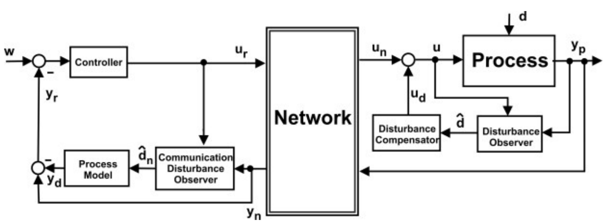

Fig. 1. Network Control Structure

The modular approach has two main advantages. First, it reduces the overall complexity of the design process, because each module can be designed independently. Second, from a practical point a view, an existing local control structure can be upgraded to a network control structure simply by adding additional modules (CDOB).

The design procedure for the Network Control Structure is further presented for the speed control of DC motor using a 2nd order model for the motor. Although the design is presented for a specific 2nd order process, the same sequence of steps can be followed for other processes of 2nd order.

B. Process modeling and design of the controller

For the DC motor, connected with an electric drive and a tachogenerator, the following well known linear model in transfer function form with null initial conditions is used:

$$\omega_m(s) = \frac{k_P}{T_a T_m s^2 + T_m s + 1} u(s) - \frac{(1+T_a)T_m / J}{T_a T_m s^2 + T_m s + 1} T_L(s) \tag{3}$$

Here ω_m is the measured speed (denoted in Fig. 1 as y_p), u is the control voltage signal, T_L is the load torque (local disturbance d), k_p is the gain of the process, T_a and T_m are time constants, J is the moment of inertia. The parameter values which will be used further on, determined based on experimental identification, are: $k_p=1\ s^{-1}V^{-1}$, $T_m=0.157$ s and $T_a=0.039$ s. To avoid introducing an additional parameter, J will be considered as part of T_L.

Next, the controller in Fig. 1 is designed assuming that the disturbances are completely compensated, meaning that the process dynamics is given only by the transfer function

$$H_u(s) = k_P / \left(T_a T_m s^2 + T_m s + 1\right) \tag{4}$$

For simplifying the design process, the second order transfer function $H_u(s)$ is reduced to a first order one

$$H_u^*(s) = 1/(Ts+1) \tag{5}$$

with the time constant T computed so that the differences of the Bode characteristics for the two transfer functions are as small as possible on the frequency range of interest. Consequently, the obtained time constant was T=0.29s.

In order to obtain a null steady state error, a PI controller is adopted for the undisturbed process model (5):

$$H_C(s) = K_p + K_i / s = K(T_i s + 1)/(T_i s) \tag{6}$$

with $K=K_p$ and $T_i=K_p/K_i$. The time constant T_i is adopted in order to compensate the dynamics of the simplified process ($T_i=T=0.29$s) and the gain K is determined by imposing a certain settling time for the resulted closed loop with

$$H(s) = \frac{H_C(s)H_u^*(s)}{1 + H_C(s)H_u^*(s)} = \frac{1}{(T_i/K)s + 1} \tag{7}$$

For an imposed settling time of 2.5s, it results that K=0.46 (settling time is four times the time constant from (7)).

C. Reduced order DOB design

The DOB will be used for load disturbance compensation (a local feedback loop like in Fig. 1). By including J into the disturbance, the local disturbance d is redefined as $x_a=T_L/J$ (relative load torque). The design steps are as follows.

First, the process model (3) is brought to the state space form:

$$\begin{bmatrix} \dot{x}_{p1}(t) \\ \dot{x}_{p2}(t) \end{bmatrix} = \begin{bmatrix} 0 & T_m^{-1} \\ -T_a^{-1} & -T_a^{-1} \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ x_{p2}(t) \end{bmatrix} + \begin{bmatrix} 0 & -1 \\ T_a^{-1} & 0 \end{bmatrix} \begin{bmatrix} u(t) \\ x_a(t) \end{bmatrix}$$

$$y_p(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ x_{p2}(t) \end{bmatrix} \tag{8}$$

where x_{p1} and x_{p2} are the states of the process, while $y_p=\omega_m$.

Second, due to the fact that the local disturbance x_a cannot be measured and has slow variations in time, it will be considered as an exogenous staircase signal modeled by

$$\dot{x}_a(t) = 0 \tag{9}$$

Consequently, for the disturbed process the following observable extended state space model holds:

$$\begin{bmatrix} \dot{x}_{p1}(t) \\ \dot{x}_{p2}(t) \\ \dot{x}_a(t) \end{bmatrix} = \begin{bmatrix} 0 & T_m^{-1} & -1 \\ -T_a^{-1} & -T_a^{-1} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ x_{p2}(t) \\ x_a(t) \end{bmatrix} + \begin{bmatrix} 0 \\ T_a^{-1} \\ 0 \end{bmatrix} u(t) \tag{10}$$

$$y_p(t) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ x_{p2}(t) \\ x_a(t) \end{bmatrix}$$

Third, in order to estimate the disturbance x_a, a reduced order DOB is built for the extended process (10). The reduced order DOB is designed as a Luenberger observer, by taking into account that state x_{p1} is available through the measured output y_p of the system ([12]). Thus, by isolating the measurable state of the system, model (10) becomes

$$\begin{bmatrix} \dot{x}_{p1}(t) \\ --- \\ \dot{x}_{p2}(t) \\ \dot{x}_a(t) \end{bmatrix} = \left[\begin{array}{c|cc} \overbrace{0}^{\mathbf{A}_{a11}} & \overbrace{T_m^{-1} \quad -1}^{\mathbf{A}_{a12}} \\ \hline -T_a^{-1} & -T_a^{-1} & 0 \\ \underbrace{0}_{\mathbf{A}_{a21}} & \underbrace{0 \quad 0}_{\mathbf{A}_{a22}} \end{array}\right] \begin{bmatrix} \overbrace{x_{p1}(t)}^{x_\alpha} \\ --- \\ x_{p2}(t) \\ \underbrace{x_a(t)}_{\mathbf{x}_\beta} \end{bmatrix} + \begin{bmatrix} \overbrace{0}^{b_{a1}} \\ -- \\ T_a^{-1} \\ \underbrace{0}_{\mathbf{b}_{a2}} \end{bmatrix} u(t)$$

$$y_p(t) = \left[\begin{array}{c|c} \underbrace{1}_{c_{a1}^T} & \underbrace{0 \quad 0}_{\mathbf{c}_{a2}^T} \end{array}\right] \cdot \begin{bmatrix} x_{p1}(t) \\ --- \\ x_{p2}(t) \\ x_a(t) \end{bmatrix} \tag{11}$$

In order to avoid using the derivative of the measured output y_p, the state of the observer is defined as:

$$\tilde{\mathbf{x}}(t) = \hat{\mathbf{x}}_\beta(t) - \mathbf{l}_a \; y_p(t) \tag{12}$$

where $l_a=[l_{a1} \; l_{a2}]^T$ will be the internal observer gain. Finally, the equations of the reduced order observer become:

$$\begin{aligned} \dot{\tilde{\mathbf{x}}}(t) = (\mathbf{A}_{a22} - \mathbf{l}_a \; \mathbf{A}_{a12})\hat{\mathbf{x}}_\beta(t) + (\mathbf{A}_{a21} - \mathbf{l}_a \; \mathbf{A}_{a11}) y_p(t) \\ + (\mathbf{b}_{a2} - \mathbf{l}_a \; b_{a1}) u(t) \end{aligned} \tag{13}$$

respectively

$$\begin{bmatrix} \dot{\tilde{x}}_1(t) \\ \dot{\tilde{x}}_2(t) \end{bmatrix} = \begin{bmatrix} -\dfrac{T_m + T_a l_{a1}}{T_a T_m} & l_{a1} \\ -\dfrac{l_{a2}}{T_m} & l_{a2} \end{bmatrix} \begin{bmatrix} \hat{x}_{p2}(t) \\ \hat{x}_a(t) \end{bmatrix} - \begin{bmatrix} \dfrac{1}{T_a} & \dfrac{1}{T_a} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ u(t) \end{bmatrix} \tag{14}$$

Forth, the DCO is designed for closing the local disturbance compensation feedback loop. For simplicity, the DCO will be considered a static gain k_a, while the design procedure is adapted from [10].

The forth design step ends the algorithmic design of the control loop, followed in a last step by the parameters calculation (l_{a1}, l_{a2} and k_a). They will be adopted in order to satisfy the static and dynamic requirements of the local closed loop system. For this, the model (3) is rewritten as

$$\begin{aligned} x_{p1}(s) &= H_u(s)u(s) + H_{xa}(s)x_a(s) \\ &= \frac{1}{T_a T_m s^2 + T_m s + 1} u(s) - \frac{(1+T_a)T_m}{T_a T_m s^2 + T_m s + 1} x_a(s) \end{aligned} \tag{15}$$

Due to the DCO the input u is:

$$u(s) = u_n(s) + k_a \hat{x}_a(s) \tag{16}$$

From the DOB and the controlled process models, the estimated disturbance is obtained as

$$\hat{x}_a(s) = \underbrace{\frac{T_m l_{a2}(T_a s + 1)}{T_m T_a s^2 + (T_m + l_{a1} T_a - T_a T_m l_{a2}) s - l_{a2} T_m}}_{H_a(s)} x_a(s) \tag{17}$$

By substituting (17) and (16) into (15) it results that

$$\begin{aligned} x_{p1}(s) = H_{xa}(s)\Big[& H_u(s)/H_{xa}(s) \cdot u_n(s) \\ & + \overbrace{(H_u(s) k_a H_a(s)/H_{xa}(s) + 1)}^{H_\alpha(s)} x_a(s) \Big] \end{aligned} \tag{18}$$

It can easily be observed that the disturbance rejection is dependent on $H_\alpha(s)$. In static conditions, for $k_a=T_m$, a full disturbance compensation is obtained because $H_\alpha(0)=0$. For the dynamic conditions, it should be taken into account that the disturbance has slow time variations, so $H_\alpha(s)$ should act as a high pass filter. This can be accomplished by appropriately choosing l_{a1} and l_{a2}. Additionally, l_{a1} and l_{a2} should be chosen in order to assure stability and to make the observer faster than the observed process. For the given process parameters, the poles of the process are p_1=-11.169 and p_2=-14.473. Taken this into account, the observer poles are adopted as p_{DOB1}=-17 and p_{DOB2}=-20, which leads to l_{a1}=-0.30 and l_{a2}=-13.26. With these values, the amplitude-frequency Bode characteristics can be drawn for H_α – Fig. 2. The figure confirms the high pass nature of $H_\alpha(s)$, rejecting low frequency disturbances. In this case, the observer's poles cannot modify the cut-off frequency, but they can modify the amplitude slope at low frequencies, ensuring a better disturbance rejection. However, it was observed that a further increase of the absolute values of the poles beyond the values mentioned before does not significantly improve the amplitude slope at low frequencies. Consequently, it can be considered that the designed local disturbance rejection loop should ensure satisfactory performances.

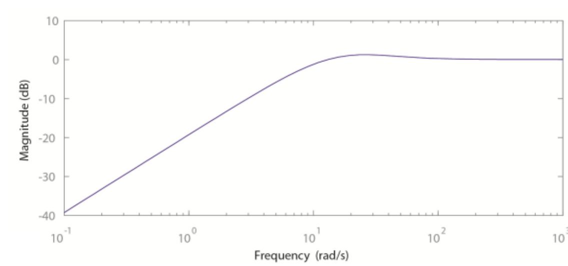

Fig. 2. Amplitude-frequency Bode characteristics for $H_\alpha(s)$.

D. Reduced order CDOB design

The CDOB will be used for delay disturbance x_n (corresponding to disturbance d_n from Fig. 1) compensation. It is designed considering that the local disturbance x_a is completely compensated by the local feedback loop. The design procedure is based on [10], but extended to the second order process, hence to a more complicated process.

Taking into account definition (1) in the form $u(t)=u_r(t)+x_n(t)$ for the process (8) with the disturbance x_a compensated, the model can be written as

$$\begin{bmatrix} \dot{x}_{p1}(t) \\ \dot{x}_{p2}(t) \end{bmatrix} = \begin{bmatrix} 0 & T_m^{-1} \\ -T_a^{-1} & -T_a^{-1} \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ x_{p2}(t) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ T_a^{-1} & T_a^{-1} \end{bmatrix} \begin{bmatrix} u_r(t) \\ x_n(t) \end{bmatrix}$$

$$y_n(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ x_{p2}(t) \end{bmatrix} \tag{19}$$

Due to digital to analog conversions u(t) is a staircase signal. This implies that x_n is a staircase signal too, constant on certain time intervals. Consequently, the model for the delay disturbance can also be defined as:

$$\dot{x}_n(t) = 0 \tag{20}$$

and the extended state space model of the process becomes

$$\begin{bmatrix} \dot{x}_{p1}(t) \\ \dot{x}_{p2}(t) \\ \dot{x}_n(t) \end{bmatrix} = \begin{bmatrix} 0 & T_m^{-1} & -1 \\ -T_a^{-1} & -T_a^{-1} & T_a^{-1} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ x_{p2}(t) \\ x_n(t) \end{bmatrix} + \begin{bmatrix} 0 \\ T_a^{-1} \\ 0 \end{bmatrix} u_r(t) \tag{21}$$

$$y_n(t) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ x_{p2}(t) \\ x_n(t) \end{bmatrix}$$

Because (21) is observable, following the same steps as in the previous section, a reduced order CDOB will be designed, which will estimate only the non-measurable states (x_{p2} and x_n). The measurable state is isolated as

$$\begin{bmatrix} \dot{x}_{p1}(t) \\ --- \\ \dot{x}_{p2}(t) \\ \dot{x}_n(t) \end{bmatrix} = \begin{bmatrix} \overbrace{0}^{A_{n11}} & | & \overbrace{T_m^{-1} \quad 0}^{A_{n12}} \\ --- & -|- & -- \quad - \\ -T_a^{-1} & | & -T_a^{-1} \quad T_a^{-1} \\ \underbrace{0}_{A_{n21}} & | & \underbrace{0 \quad 0}_{A_{n22}} \end{bmatrix} \begin{bmatrix} \overbrace{x_{p1}(t)}^{x_\alpha} \\ --- \\ x_{p2}(t) \\ \underbrace{x_n(t)}_{x_\gamma} \end{bmatrix} + \begin{bmatrix} \overbrace{0}^{b_{n1}} \\ -- \\ T_a^{-1} \\ \underbrace{0}_{b_{n2}} \end{bmatrix} u_r(t)$$

$$y_n(t) = \begin{bmatrix} \underbrace{1}_{c_{n1}^T} & | & \underbrace{0 \quad 0}_{c_{n2}^T} \end{bmatrix} \cdot \begin{bmatrix} x_{p1}(t) \\ --- \\ x_{p2}(t) \\ x_n(t) \end{bmatrix} \tag{22}$$

Again an intermediate state is defined

$$\bar{\mathbf{x}}(t) = \hat{\mathbf{x}}_\gamma(t) - \mathbf{l}_n\ y_n(t) \tag{23}$$

where $\mathbf{l}_n=[l_{n1}\ l_{n2}]^T$ will be the internal observer gain. The reduced order observer can now be written as:

$$\dot{\bar{\mathbf{x}}}(t) = (\mathbf{A}_{n22} - \mathbf{l}_n\ \mathbf{A}_{n12})\hat{\mathbf{x}}_\gamma(t) + (\mathbf{A}_{n21} - \mathbf{l}_n\ \mathbf{A}_{n11}) y_n(t) + (\mathbf{b}_{n2} - \mathbf{l}_n\ b_{n1}) u_r(t) \tag{24}$$

Finally, the detailed equations for the reduced order observer are:

$$\begin{bmatrix} \dot{\bar{x}}_1 \\ \dot{\bar{x}}_2 \end{bmatrix} = \begin{bmatrix} -\dfrac{T_m + l_{n1}T_a}{T_aT_m} & \dfrac{1}{T_a} \\ -\dfrac{l_{n2}}{T_m} & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_2 \\ \hat{x}_n \end{bmatrix} - \begin{bmatrix} \dfrac{1}{T_a} & \dfrac{1}{T_a} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_{p1}(t) \\ u_r(t) \end{bmatrix} \tag{25}$$

The estimated disturbance $\hat{x}_n$ is further fed through the $x_n \rightarrow y_p$ channel of the process model given by $H_u(s)$. The output signal y_r that reaches the controller is determined as

$$y_r(s) = y_p(s) - y_d(s) = y_p(s) - H_u(s)\hat{x}_n(s) \tag{26}$$

Considering that

$$y_p(s) = H_u(s)(x_n(s) + u_r(s)) \tag{27}$$

and by plugging (27) into (26) it results that the disturbance is completely rejected on the controller side as $\hat{x}_n \rightarrow x_n$:

$$y_r(s) = H_u(s)u_r(s) \tag{28}$$

At this stage, the design of the delay disturbance compensation structure reduces to adopting the observer gains l_{n1} and l_{n2} so that the estimated disturbance follows the real disturbance as fast as possible, while also assuring the stability of CDOB. This can be achieved by first expressing as function of the real disturbances which affect the process – x_n and x_a – based on the CDOB and process models with both disturbances:

$$\hat{x}_n(s) = H_n(s)x_n(s) + \underbrace{(T_aT_ms + T_m)H_\alpha(s)}_{H_\beta(s)} H_n(s)x_a(s) \tag{29}$$

with

$$H_n(s) = -\frac{1}{(T_mT_a/l_{n2})s^2 + (T_m/l_{n2} + l_{n1}T_a/l_{n2})s + 1} \tag{30}$$

By analyzing (29) it is obvious that x_n is estimated correctly only if the following conditions are met ([10]):

$$\begin{cases} Condition\ 1: |H_n(j\omega)| \rightarrow 1 \\ Condition\ 2: |H_\beta(j\omega)H_n(j\omega)| \rightarrow 0 \\ Condition\ 3: CDOB\ stable\ \&\ faster\ than\ process \end{cases} \tag{31}$$

E. Full order CDOB design

For comparison purposes, the CDOB will be also designed as a full order observer. The extended process model (21) will again be used, but this time the observer will estimate all three states. The full order CDOB can be written directly as

$$\begin{bmatrix} \dot{\hat{x}}_{p1}(t) \\ \dot{\hat{x}}_{p2}(t) \\ \dot{\hat{x}}_n(t) \end{bmatrix} = \begin{bmatrix} -l_{n1} & T_m^{-1} & 0 \\ -T_a^{-1} - l_{n2} & -T_a^{-1} & T_a^{-1} \\ -l_{n3} & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_{p1}(t) \\ \hat{x}_{p2}(t) \\ \hat{x}_n(t) \end{bmatrix} + \begin{bmatrix} 0 \\ T_a^{-1} \\ 0 \end{bmatrix} u_r(t) + \begin{bmatrix} l_{n1} \\ l_{n2} \\ l_{n3} \end{bmatrix} x_{p1}(t)$$

$$\hat{y}_n(t) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}_{p1}(t) \\ \hat{x}_{p2}(t) \\ \hat{x}_n(t) \end{bmatrix} \tag{32}$$

The disturbance $\hat{x}_n$, estimated by the CDOB, is again fed through the $x_n \rightarrow y_p$ channel of the process model given by $H_u(s)$, and y_r is determined as in (26). The design of the delay disturbance compensation structure refers in this case to adopting the observer gains l_{n1}, l_{n2}, and l_{n3}. In determining these parameters (29) is used, but now H_n has the form:

$$H_n(s) = \frac{-l_{n3}}{T_aT_ms^3 + T_m(1 + l_{n1}T_a)s^2 + (l_{n1}T_m + l_{n2}T_a + 1)s + l_{n3}} \tag{33}$$

For a good estimation of $\hat{x}_n$, conditions (31) are mandatory.

F. Full order vs. reduced order CDOB - design issues

In designing the CDOB, either the reduced order or the full order version, conditions (31) have to be met.

The first condition implies that H_n should have an amplitude close to unity for a frequency domain as large as possible. This is required so that $\hat{x}_n$ is as close as possible to x_n on a large enough frequency domain. Ideally, this would mean high cut-off frequencies and consequently high observer gains. However, in digital implementation high gains usually lead to large numerical errors (peaking phenomenon), so in practical applications a compromise solution should be adopted.

The second condition implies that across the imaginary axes H_nH_β should have amplitude as small as possible. This means that x_a should not influence the estimation of x_n. Through H_n, this condition is influenced by the way the first condition is handled.

The third condition is the least restrictive, and requires only that the poles of the observer have negative real part, with absolute values larger than the process poles.

In designing a CDOB in the context of the control system from Fig. 1, where the process and controller are the ones described in Section II B, an analysis has to be done for finding the most suitable cut-off frequency value ω_n for H_n. The network block introduces a time-varying delay and packet loss (Fig. 5). The reference signal w will consist in an upward step and a downward step.

Fig. 3 shows the amplitude-frequency Bode characteristics of H_n and H_nH_β for three chosen cut-off frequencies (37 rad/s, 370 rad/s and 18000 rad/s), for the reduced and full order CDOB, considering a sample time of h=1ms. It can be observed that from the point of view of condition 1, the largest value of ω_n is preferred, while from the point of view of condition 2, the smallest value of ω_n is preferred. The largest cut-off frequency cannot be considered as a valid choice because it implies the disturbance influence of x_a on the estimation of x_n is amplified instead of rejected. The differences between the two CDOBs are small.

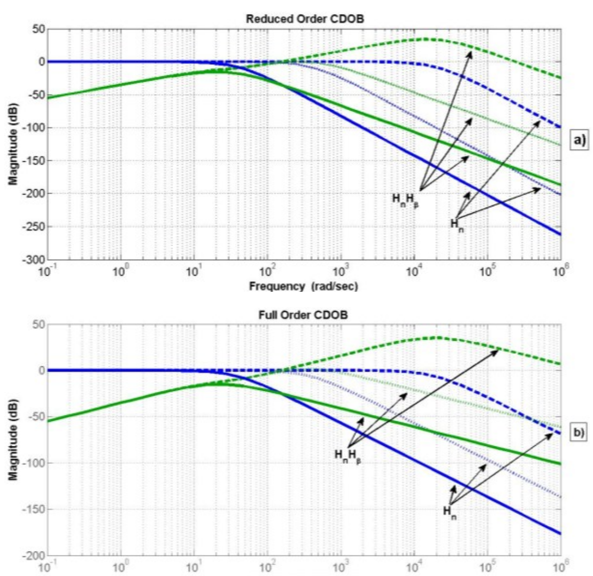

Fig. 3. Amplitude-frequency characteristics for the H_n and H_nH_β for the reduced order CDOB (a) and full order CDOB (b), when choosing a cut-off frequency of ~37 rad/s (solid line), ~370 rad/s (dotted line), and ~18000 rad/s (dashed line).

Next, Fig. 4 illustrates time domain estimation results of x_n for the two remaining cut-off frequencies (37 rad/s and 370 rad/s) for both types of CDOBs. The cut-off frequency of 370 rad/s leads to an unwanted peaking phenomena due to numerical errors, for both CDOBs. The 37 rad/s cut-off frequency leads to much better results, so that the peaking phenomenon is avoided. The full order CDOB manages to produce a smooth estimation of x_n, while the reduced order CDOB still has some noise in the estimation due to numerical errors. This is due to the fact that for a given cut-off frequency, the gains of the reduced order CDOB are considerable lager than those of the full order one.

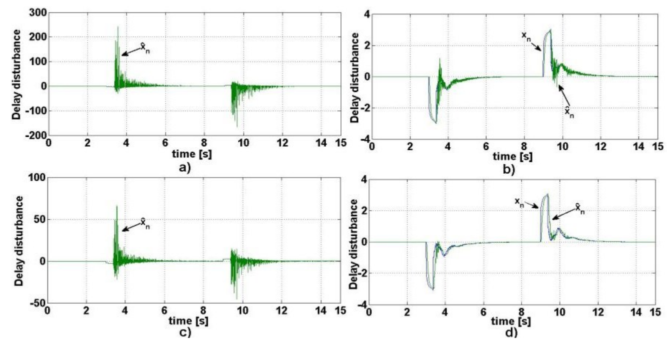

Fig. 4. Estimation of x_n done by the reduced order CDOB (a,b) and full order CDOB (c,d), when choosing the cut-off frequency of ~370 rad/s (a,c) and ~37 rad/s (b,d).

It should also be mentioned that in all discussed cases condition 3 was respected. Moreover, in obtaining the simulation results from Fig. 4, several stiff differential equation solvers were used in Matlab/Simulink (e.g. ode15, ode14x), and it was observed that the mentioned numerical errors cannot be avoided.

Finally, it can be concluded that the most suitable choice for the presented case study is to use a full order CDOB with a cut-off frequency ω_n=37 rad/s. The obtained observer gains are l_{n1}=102.04, l_{n2}=410.01 and l_{n3}=461.43.

III. SIMULATIONS AND EXPERIMENTS

In this section the designed network control system is tested in simulations and experiments. The controller and process models used are those from Section II B, the DOB and DCO are the ones from Section II C, while the CDOB used is the full order CDOB designed in Sections II E and F.

The considered scenario assumes pulse reference signals of the form $w(t)=w_0\cdot[\sigma(t-t_0) - \sigma(t-t_1)]$. The adopted sampling period is of 1 ms. This value is sufficient for controlling the process in real-time. In order to emulate the behavior of real-time TCP/IP networks the network transmission block (NTB) from [13] was used.

The DC motor process considered in the experiments is controlled through an electric drive within the voltage (control signal) domain of ±24 V, has a moment of inertia of $5.18 \cdot 10^{-6}$ kg m^2 and it can reach a maximum speed (controlled output) of 4000 rpm. The motor speed is measured through a tachogenerator, linear on the entire speed domain. The actual control structure was developed in the Matlab/Simulink environment and implemented on to the dSPACE system. The experimental data was collected on a computer (PC) connected to a dSPACE system. The communication network is emulated also on the dSPACE system through an algorithm which implements the NTB. Fig. 5 illustrates the entire structure (experimental setup).

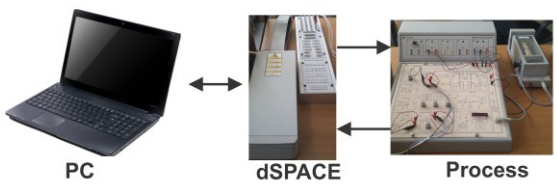

Fig. 5. Experimental setup for the Network Control System.

A. Modeling network transmissions

The algorithm used in the NTB implements a buffer which is continuously shifted, filled and emptied at each sample moment, according to the instant values of the time varying delay, packet loss and handling strategy for the received network packets ([13]). The distributions for the time varying delay and packet loss values can be obtain using real network measurements or different stochastic models. For the case study presented in this paper the values of the time varying delay τ and packet loss flag p are generated as uniformly distributed pseudo-random numbers which are in agreement with measurements on a real TCP/IP network ([11]). Fig. 6 shows the time variation of τ and p on a two second time window. The delay values are between 180 ms and 220 ms with an average of 200 ms. The flag p can take two values: 1 for a received packet and 0 for a lost one.

As a remark it is important to mention that, besides the results presented in this paper, additional experiments were conducted for different delay and packet loss distributions and domain values, and it was observed that the control objective is achieved for delay values of less than 1 s and for packet loss below 30 %.

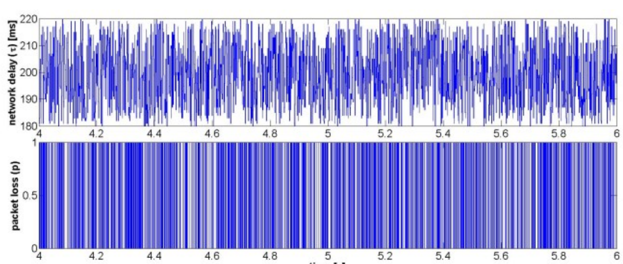

Fig. 6. Generated network delay and network packet loss.

B. Simulation results

The results from Fig. 7 show the system's response for the considered scenario. The result for local control confirms that the PI controller assures good performances: no overshoot and a settling time closed to the imposed one. When adding the network in the control loop the system becomes oscillatory. The extension of the control system with the CDOB structure leads to a system response close to the response for the local control, while eliminating the oscillations induced by the network. The improved response is due to the CDOB structure's capability to estimate and reject the delay disturbance (Fig. 8).

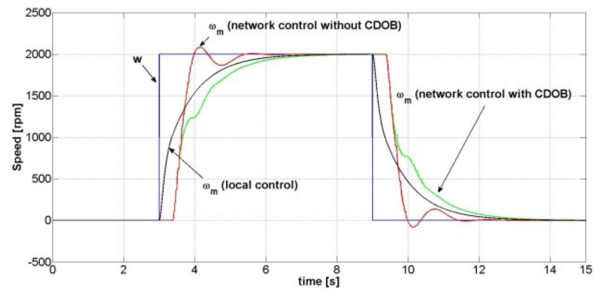

Fig. 7. Comparative simulation results of the control system

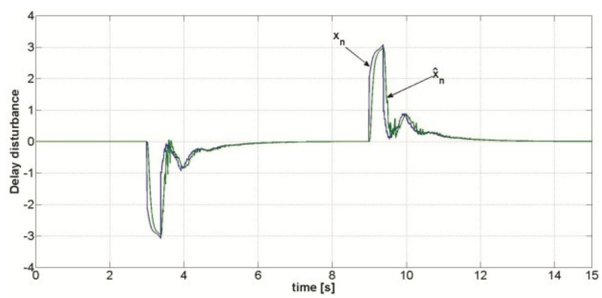

Fig. 8. Delay disturbance (x_n) estimation - simulations.

C. Experimental results

The results obtained through experiments (Fig. 9, 10) are in agreement with the simulation results. Although the oscillations induced by the network in the system's response are larger, when using the CDOB structure the oscillations are still successfully eliminated.

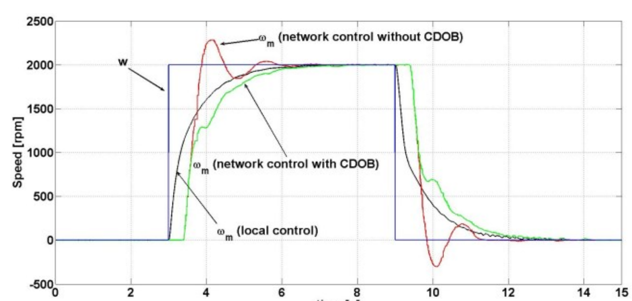

Fig. 9. Comparative experimental results of the control system.

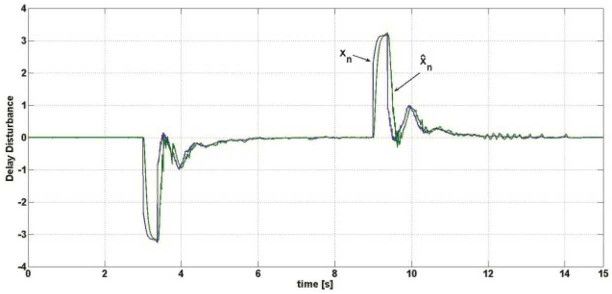

Fig. 10. Delay disturbance (x_n) estimation - experiments.

IV. CONCLUSIONS

To compensate the shortcomings associated with time delays and packet loss in NCSs, control structures based on local and remote placed observers can be used. The CDOB based method presented in [10], for first order processes, is extended in the current paper for second order processes. The additional degrees of freedom involve an elaborate design, and require a more extensive analysis in order to set the observers' parameters (cut-off frequencies). The analysis also captures a peaking phenomenon (not shown in [10]), which, from a practical point of view, limits the range of the design parameters. Moreover, a comparative analysis is conducted for determining which type of observer ensures the best performances (full order versus reduced order). The full order CDOB proved to be more efficient.

The designed Network Control System is tested through simulations and experiments. Additionally, because the usage of standard delay blocks from Matlab/Simulink leads to a false image of what happens on a real network, for validations a Network Simulator was used, implemented as a user defined NTB in Simulink ([13]).

As future work, the network control structure should be improved as to increase the robustness of the system.

REFERENCES

[1] J. P. Hespanha, P. Naghshtabrizi, and Y. Xu, "A Survey of Recent Results in Networked Control Systems," Proc. IEEE, vol. 95, no. 1, pp. 138–162, Jan. 2007.

[2] S. Zampieri, "Trends in Networked Control Systems," in Proc. 17th IFAC World Congress, Seoul, 2008, pp. 2886–2894.

[3] P. F. Hokayem and C.T. Abdallah, "Inherent Issues in Networked Control Systems: A Survey," in Proc. American Control Conference, Boston, 2004, pp. 4897–4902.]

[4] C.-L. Lai and P.-L. Hsu, "Design the Remote Control System With the Time-Delay Estimator and the Adaptive Smith Predictor", IEEE Trans. Indus. Informatics, vol. 6, no. 1, pp. 73- 80, Feb. 2010.

[5] A. Onat, T. Naskali, E. Parlakay, O. Mutluer, "Control Over Imperfect Networks: Model-Based Predictive Networked Control Systems," IEEE Trans. Indus. Electron., vol. 58, no. 3, pp. 905–913, Mar. 2011.

[6] H. Li, Z. Sun, M.-Y. Chow, and F. Sun, "Gain-Scheduling-Based State Feedback Integral Control for Networked Control Systems," IEEE Trans. Ind. Electron., vol. 58, no. 6, pp. 2465–2472, Jun. 2011.

[7] J. Nilsson, "Real-time control systems with delay," Ph.D. Thesis, Lund Institute of Technology, 1998.

[8] W. Hu, G. Liu, D. Rees, "Event-Driven Network Predictive Control," IEEE Trans. Indus. Electron., vol. 59, no. 3, pp. 905-913, 2011.

[9] M. Hou and P.C. Müller, "Design of Observers for Linear Systems with Unknown Inputs," IEEE Trans. on Autom. Control, vol. 37, no. 6, pp. 871- 875, Jun. 1992.

[10] K. Natori, T. Tsuji, K. Ohnishi, A. Hace, and K. Jezernik, "Time-Delay Compensation by Communication Disturbance Observer for Bilateral Teleoperation Under Time-Varying Delay," IEEE Trans. Indus. Electron., vol. 57, no. 3, pp. 1050–1062, Mar. 2010.

[11] O. Stefan, T.-L. Dragomir, A. Codrean, I. Silea, "Issues of identifying, estimating and using delay times in telecontrol systems based on TCP/IP networks," in Proc. 2nd IFAC Symposium on Telematics Applications, Timisoara, 2010, pp. 143-148.

[12] D. G. Luenberger, "An Introduction to Observers," IEEE Trans. Autom. Control, vol. 16, no. 6, pp. 596–602, Dec. 1971.

[13] O. Stefan, A. Codrean, T.-L. Dragomir, "A Nonlinear State Space Model of Network Transmissions in a Network Control System," Journal of Control Engineering and Applied Informatics, vol. 13, no. 4, pp.58- 63, 2011.