IMPROVING THE CONTROL PERFORMANCE OF A REAL-TIME DISTRIBUTED CONTROL SYSTEM UNDER VARIABLE SAMPLING TO ACTUATION DELAY

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ABSTRACT
This paper analyses a method to improve the control performance of a real-time distributed control system under variable sampling to actuation delay. The method uses models of the plant that take into account the fractional dead-time to model the variable delay. The resulting controller is slower than the ordinary one but gives better control performance.

KEY WORDS
Real-time distributed control, adaptive control.

1. Introduction

Distributed control systems are widely used in embedded applications. The distribution of the control system induces jitter in the sampling and in the actuation moment introducing a variable delay between the sampling and the actuation moment. The variable sampling to actuation delay introduced by the distributed architecture of the system leads to control performance degradation depending on the amount of the jitter and the delay [1]-[6]. References [7], [8] propose a new method for identifying and modeling systems subject to variable sampling to actuation delay by modeling it as a fractional dead-time.

The present work analyses the control performance of two control systems, of first and second order, obtained using identification models with and without taking into account the variable sampling to actuation delay. The results show that the models with fractional dead-time, although making the closed loop system slower, allow it to remain stable even when subject to severe sampling to actuation delay conditions.

2. The system

Figure 1 presents the block diagram of the real-time distributed control system.

The system has three nodes: sensor node, actuation node and controller node. The nodes are connected using the CAN bus. The communication scheme followed is depicted in figure 2.

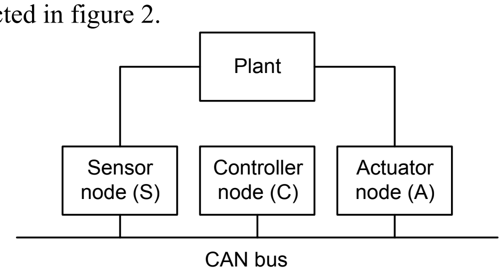

Fig. 1. Block diagram of the distributed control system.

The sensor sends a message M1 with the sample value to the controller node that computes the actuation value and sends it and the actuation order to the actuation node using message M2.

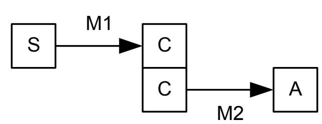

Fig. 2. Communication model scheme for the system.

The system was simulated using TrueTime, a MATLAB/Simulink based simulator for real-time control systems [9]-[11]. The TrueTime simulator allows co-simulation of controller task execution in real-time kernels, network transmissions and continuous plant dynamics. This tool was chosen because of its flexibility and as a base for future tests using a network scheduler [17].

Each node of the system was implemented using a TrueTime Kernel block and the CAN bus was implemented with a TrueTime Network block [12].

Tests were made for two different plants with transfer functions of first and second order given by (1) and (2), respectively.

$$\frac{Y(s)}{U(s)} = \frac{0.05}{s+0.05} \tag{1}$$

$$\frac{Y(s)}{U(s)} = \frac{1.5}{s^2+0.5s+1.5} \tag{2}$$

3. The adaptive controller

The controller used was a pole placement adaptive controller. The adaptive controller was implemented in MATLAB inside the TrueTime Kernel of the controller node.

2.1 System Identification

The generic form of the discrete time transfer function to be modeled is given by (3) where polynomials A and B are given by (4) and (5) and K is the discrete dead-time.

$$G(q^{-1}) = q^{-K}\frac{B(q^{-1})}{A(q^{-1})} \tag{3}$$

$$A(q^{-1}) = 1 + a_1 q^{-1} + \ldots + a_n q^{-n} \tag{4}$$

$$B(q^{-1}) = b_0 + b_1 q^{-1} + \ldots + b_m q^{-m} \tag{5}$$

The system identification was based on two different models, the usual one that ignores the variable sampling to actuation delay and another, modeling that delay as fractional dead-time, as presented in [7], [8]. In the last case the model proposed for the SISO (Single Input Single Output) system is given by (6) and (7),

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t-\tau) \tag{6}$$

$$y(t) = x(t) \tag{7}$$

where τ represents the variable delay which can be considered as a dead-time. If the delay is bounded by the sampling period h, τ < h, the discrete model can be represented by (8),

$$y(kh+h) = \Phi y(kh) + \Gamma_0 u(kh) + \Gamma_1 u(kh-h) \tag{8}$$

where

$$\Phi = e^{Ah} \tag{9}$$

$$\Gamma_0 = \int_0^{h-\tau} e^{As} ds B \tag{10}$$

$$\Gamma_1 = e^{A(h-\tau)} \int_0^{\tau} e^{As} ds B \tag{11}$$

The discrete transfer function is given by (12).

$$G(q) = \begin{bmatrix} 1 & 0 \end{bmatrix} (qI-\Phi)^{-1}(\Gamma_0 + \Gamma_1 q^{-1}) \tag{12}$$

For the first order system this leads to (13) and (14) for models 1 and 2, respectively. The parameters of the models are of the form v_{xyz} where x identifies the order of the model, y the type of the model and z the parameter for that model. Model 1 corresponding to the ordinary system identification ignoring the variable delay effect and model 2 for the identification that models the variable sampling to actuation delay as a fractional dead-time. The parameters of model 2 vary according to the variable delay introduced by the system. For model 1 the changes introduced by the variable sampling to actuation delay are reflected in the values of the parameters identified.

$$G_{f1}(q^{-1}) = \frac{b_{111}q^{-1}}{1-a\ q^{-1}} \tag{13}$$

$$G_{f2}(q^{-1}) = \frac{b_{121}q^{-1} + b_{122}q^{-2}}{1-a\ q^{-1}} \tag{14}$$

For the second order system the expressions for models 1 and 2 are given by (15) and (16).

$$G_{s1}(q^{-1}) = \frac{b_{211}q^{-1} + b_{212}q^{-2}}{1-a_{211}q^{-1} - a_{212}q^{-2}} \tag{15}$$

$$G_{s2}(q^{-1}) = \frac{b_{221}q^{-1} + b_{222}q^{-2} + b_{223}q^{-3}}{1-a_{221}q^{-1} - a_{222}q^{-2}} \tag{16}$$

Looking at (14) and (16), obtained for model 2, and comparing them with the ones obtained for model 1, (13) and (15), it can be seen that model 2 presents an extra zero, that doesn't exist when τ=0.

The discrete functions for the models were obtained using the parametric-model ARX (Auto-Regressive with an eXogenous signal) [13] that is appropriate to operate with a control function of the pole-placement type. The system parameters were estimated using the least squares criterion and a recursive implementation using forgetting factor was adopted to run online during the simulation. The regressors for the first order system, model 1 and 2, are given in (17) and (18), respectively, and for the second order system in (19) and (20).

$$y_{11}(k) = \begin{bmatrix} y_{11}(k-1) & u_{11}(k-1) \end{bmatrix} \tag{17}$$

$$y_{12}(k) = \begin{bmatrix} y_{22}(k-1) & u_{12}(k-1) & u_{12}(k-2) \end{bmatrix} \tag{18}$$

$$y_{21}(k) = \begin{bmatrix} y_{21}(k-1) & y_{21}(k-2) & u_{21}(k-1) & u_{21}(k-2) \end{bmatrix} \tag{19}$$

$$y_{22}(k) = \begin{bmatrix} y_{22}(k-1) & y_{22}(k-2) & u_{22}(k-1) & u_{22}(k-2) & u_{22}(k-3) \end{bmatrix} \tag{20}$$

2.2- The Control Function

The pole placement technique was used for the control function. It allows for the closed-loop response of the system to be totally specified in advance. The closed-loop behaviour for the two systems was determined by the appropriate choice of the values for the poles of the closed-loop transfer function. An observer polynomial, with faster dynamics was also chosen. For the first order system the closed-loop pole was chosen as α_m=0.2Hz and the observer pole as α_o=0.4Hz. For the second order system the closed-loop characteristic polynomial has bandwidth w_m=1.8 rad/s and damping factor z_m=0.7, the observer polynomial has bandwidth w_o=3.6 rad/s and damping factor z_o=0.7. The parameters of the control functions were obtained by directly solving the Diophantine's equation for each of the systems and models. The resulting control functions are given for the first order system in (21) and (22) for models 1 and 2, respectively.

$$u_{11}(k) = t_{10}(r_{ef}(k) - a_{obs}r_{ef}(k-1)) - s_{10}y(k) - s_{11}y(k-1)\ldots + u_{11}(k-1) \quad (21)$$

$$u_{12}(k) = t_{20}(r_{ef}(k) - a_{obs}r_{ef}(k-1)) - s_{20}y(k) - s_{21}y(k-1)\ldots - (r_{21}-1)u_{12}(k-1) + r_{21}u_{12}(k-2) \quad (22)$$

For the second order system the control function was obtained in a similar way but the equations are not presented because of their extension.

4. Tests' description

The sampling period was chosen following the rule of thumb from [14]. For first order systems the number of samples per rise time, N_r, should be between 4 and 10 and for second order systems the product between the natural frequency and the sampling period should be between 0.2 and 0.6. Tests were made for the limits and the middle of the intervals given by the rule of thumb. This paper presents the results obtained for h=2.8s for the first order system and h=0.33s for the second order system, corresponding to the superior limit of the intervals. This choice corresponds to the worst cases for the degradation of the control performance as shown in [15]. For more results about the 1st order system consult [16]. For the sampling periods chosen several tests are presented with different sampling to actuation delays. In all the tests the sampling jitter is equal to zero. The sampling to actuation delay introduced is variable, following a predefined distribution. Two of the sequences were obtained using the MATLAB rand function distributed over 75% and 100% of the sampling interval and the other one is based in the gamma distribution that was modified to concentrate the values in the upper half of the sampling period. The variable sampling to actuation delay obtained using the gam sequence is shown in figures 3 and 4, for the first and the second order systems, respectively.

The reference test accounts for the MAC (Medium Access Control) induced delay and for the computing delay which are constant throughout the test and equal to 8.2ms for the 1st order system and to 0.76ms for the 2nd order system.

The forgetting factor used for system identification with model 2 is equal to 0.99.

5. Tests' results

The results of the control performance are presented in tables 1 and 2 that reports the ISE (Integral of the Square Error) computed for each test.

Mod 1 refers to the model obtained ignoring the variable sampling to actuation delay effects and Mod 2 refers to the model with fractional dead-time to account for the variable sampling to actuation delay.

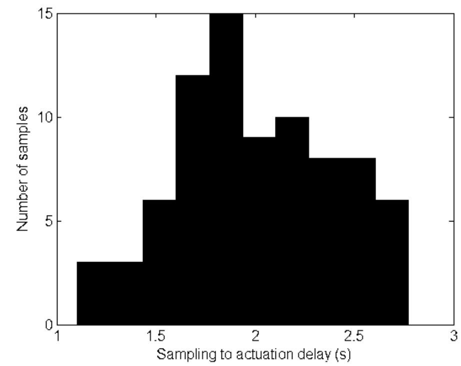

Fig. 3. Sampling to actuation delay for sequence gam, 1st order system.

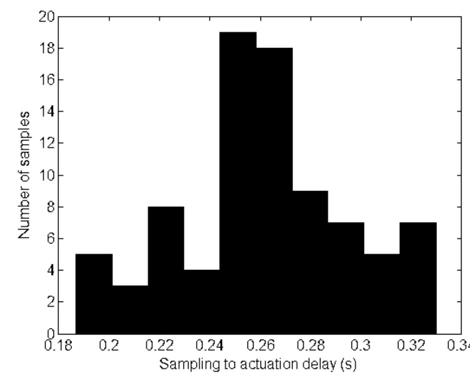

Fig. 4. Sampling to actuation delay for sequence gam, 2nd order system.

ISE computes the integral the squared error covering all the samples of the test except those of the start-up. S-A delay refers to the sampling to actuation delay.

S-A delay	ISE	
	Mod 1	**Mod 2**
Ref.	33.3	33.4
Rd75	42.1	35.9
Rd100	249.7	49.2
Gam	5.8e3	46.8

TABLE 1. MEAN SQUARE ERROR FOR THE 1ST ORDER SYSTEM.

S-A delay	ISE	
	Mod 1	**Mod 2**
Ref.	6.2	6.2
Rd75	8.2	8.0
Rd100	9.0	8.0
Gam	8.7	8.4

TABLE 2.MEAN SQUARE ERROR FOR THE 2ND ORDER SYSTEM.

For the first order system ISE was computed between t=70s and t=224s. For the second order system ISE was computed between t=9.9s and t=26.4s.

Figures 5 to 8 present the control signals for the tests using sequences rd75 and gam with the first order system. Figures 9 and 10 present the control signals for the test using the gam sequence for the second order system.

The analysis of the ISE values presented for models 1 and 2 in tables 1 and 2 shows that for the reference test the models perform in the same way. For the other tests the ISE value is always smaller for model 2.

The difference between the control performance of model 1 and model 2 his bigger when the variable sampling to actuation delay is higher and is very significant when modeling the first order system.

In the test presented in figures 7 and 8 model 1 is not able to model the behaviour of the system in the presence of the variable sampling to actuation delay resulting in heavy oscillations in the output signal. For the second order system the test presented in figures 9 and 10 shows some small oscillations but unlike the test for the first order system the output is able to follow the reference.

To understand the behaviour of the controllers when modeling the first and the second order systems with models 1 and 2 tables 3, 4 and 5 are presented. These tables present the parameters identified during the tests. Table 3 refers to the test with the first order system and tables 4 and 5 refer to the second order system.

The first row of the tables presents the theoretical values obtained by the transformation of the continuous transfer function of the system to the discrete one.

The results presented in tables 3 and 4 show that the denominator parameters' are generally better identified by model 2 for the 1st and 2nd order systems.

The evolution of the parameters' identification with time is shown in figures 11 and 12 for the tests reported in figures 7 and 8. It should be noted that the parameters' identification with model 2 stabilizes faster than the one obtained with model 1.

For the second order system the parameters' identification stabilizes around the same sample for both models. Figures are not presented for this case due to lack of space.

As the control function is based on the pole-placement technique the quality of the identification of the poles is directly reflected on the control performance (compare tables 1 and 2 with tables 3 and 4). It can also explain the dramatic effect of the variable sampling to actuation delay in the first order system as the controller relies on a single parameter that is better identified with model 2.

For the second order system the results are better with model 2 but the difference between the performance of models 1 and 2 is not so big.

6. Conclusions

An adaptive distributed control system was tested under variable sampling to actuation delay. Two different

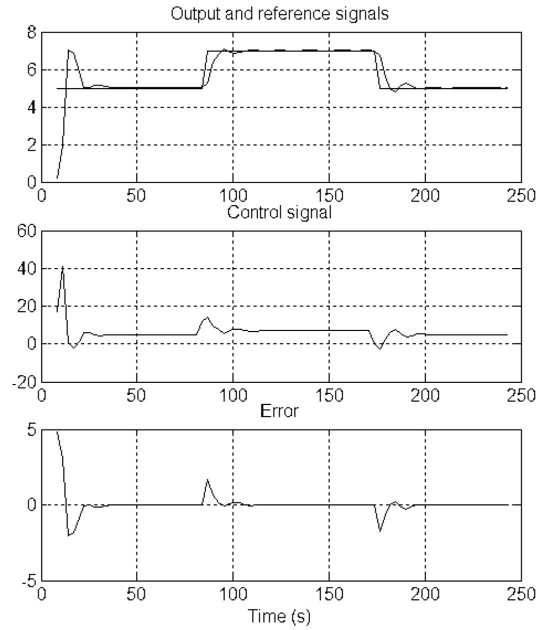

Fig. 5. Control signals for rd75 with model 1 (1st order).

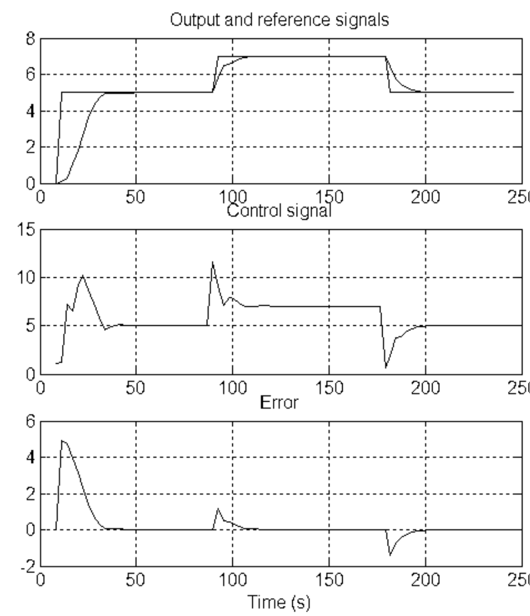

Fig. 6. Control signals for rd75 with model 2 (1st order).

	Denominator		Numerator		
	Mod 1	Mod 2	Mod 1	Mod 2	
Jitter	a111	a121	b111	b121	b122
T	-0.869	---	0.131	---	---
Ref.	-0.869	-0.869	0.131	0.130	0.001
Rd75	-0.883	-0.866	0.118	0.104	0.031
Rd100	-0.934	-0.874	0.085	0.044	0.083
Gam	-0.681	-0.867	0.030	0.041	0.092

TABLE 3. PARAMETERS IDENTIFIED AT T=232.4S DURING THE TESTS FOR THE 1ST ORDER SYSTEM.

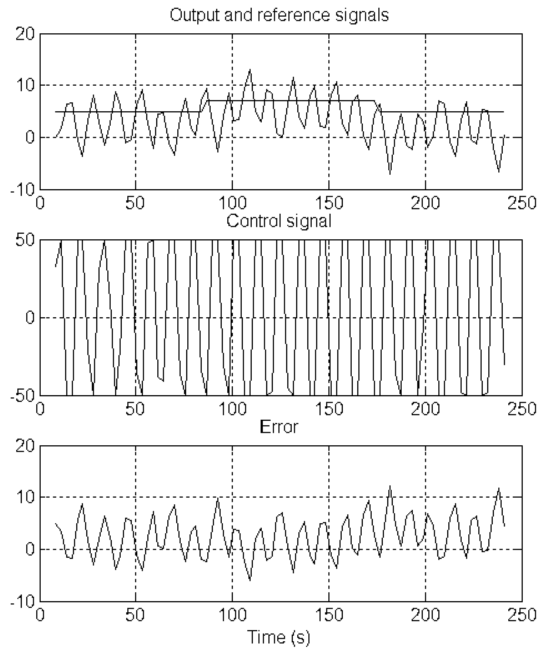

Fig.7. Control signals for gam with model 1 (1st order).

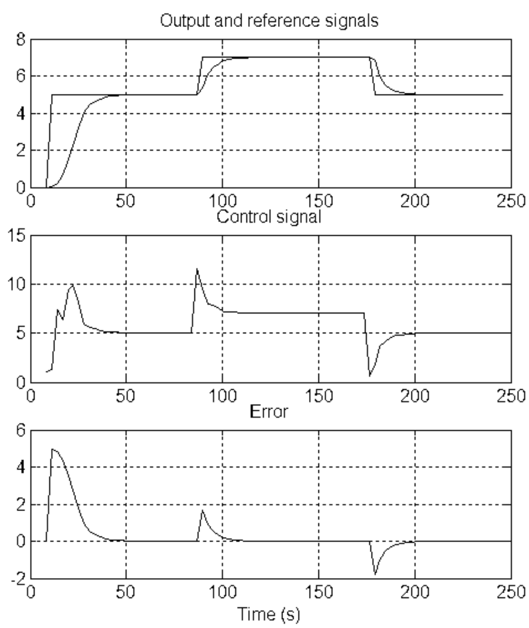

Fig.8. Control signals for gam with model 2 (1st order).

Jitter	Denominator			
	Model 1		Model 2	
	a211	a212	a221	a222
T	-1.699	0.848	---	---
Ref.	-1.697	0.846	-1.696	0.845
Rd75	-1.706	0.851	-1.692	0.837
Rd100	-1.703	0.846	-1.701	0.846
Gam	-1.803	0.929	-1.696	0.845

TABLE 4. DENOMINATOR PARAMETERS IDENTIFIED AT T=27.4S FOR THE 2ND ORDER SYSTEM.

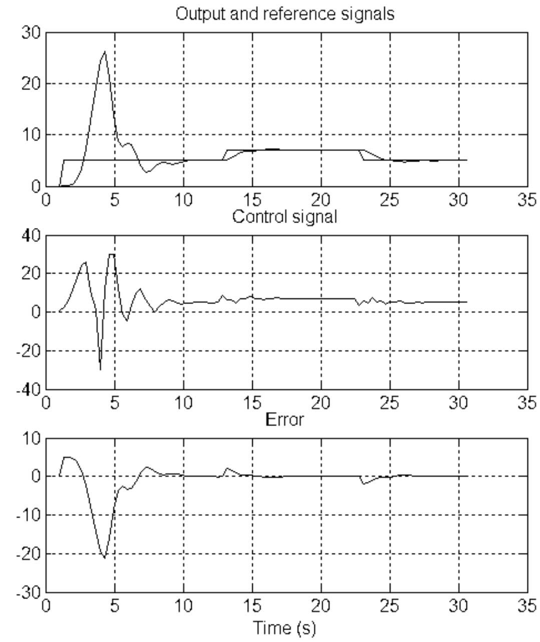

Fig. 9. Control signals for gam with model 1 (2nd order).

Jitter	Numerator				
	Model 1		Model 2		
	b211	b212	b221	b222	B223
T	0.076	0.072	---	---	---
Ref.	0.072	0.077	0.072	0.076	0.001
Rd75	0.027	0.118	0.021	0.113	0.013
Rd100	0.020	0.124	0.015	0.112	0.016
Gam	-0.008	0.132	0.008	0.087	0.055

TABLE 5. NUMERATOR PARAMETERS IDENTIFIED AT T=27.4S FOR THE 2ND ORDER SYSTEM.

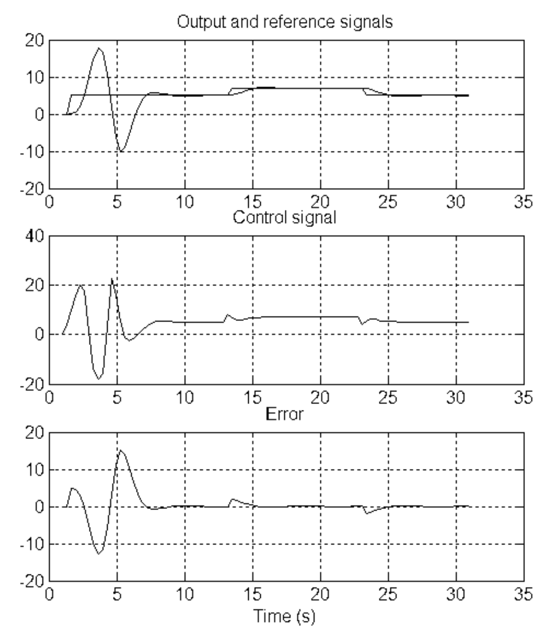

Fig. 10. Control signals for gam with model 2 (2nd order).

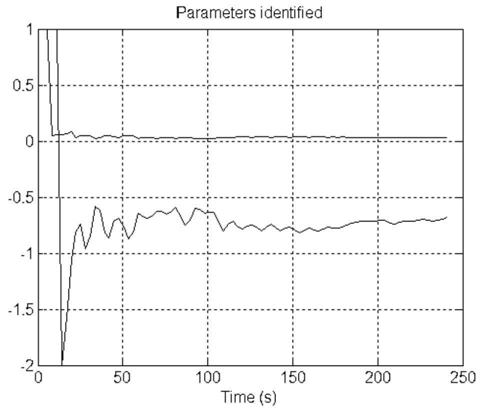

Fig. 11. Evolution of the identification of the parameters during the test reported in fig. 7.

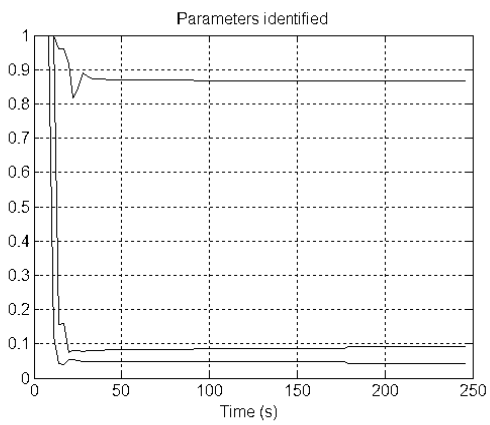

Fig. 12 Evolution of the identification of the parameters during the test reported in fig. 8.

models were used to identify the system, model 1 ignoring the variable sampling to actuation delay effects and model 2 modeling it as a fractional dead-time.

The results obtained showed that model 2 allows a better identification of the system that is directly reflected in the control performance quality because the control function used is of the pole-placement type.

The controllers implemented using the method proposed can operate with sampling periods as high as recommended by the rules of thumb with control performances that otherwise can not be obtained using model 1 for the same sampling period.

The use of longer sampling periods with acceptable control performance values allows more flexibility to the network schedulers used in distributed architectures [17] where several control systems share the same physical network.

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