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H1 Fieldbus Network Delay; A Digital Pole Placement Control Design

Hesham Abdel-Ghaffar
Invensys Engineering & Service
New Maadi, Cairo, Egypt

Sherif Hammad
Mentor Graphics
sherif_hammad@mentor.com

Ahmed Zaki
Faculty of Engineering
Ain Shams University

Abstract- This paper presents a pole-placement based control algorithm to treat ISA Fieldbus H1 delay problems. A digital network delay model is embedded with the process model in order to design a suitable closed-loop controller. The effect of different values of network delay against sampling time is analyzed. Pole-placement technique should not simplify zeros in order to achieve stability in closed-loop. Simulation results show the efficiency of the proposed control algorithm. It also gives a preliminary study on the effect of network delay jitter on closed loop performance.

Index Terms- Pole-placement, Foundation Fieldbus H1, Dead time, Frame transmission time and Throughput.

1. Introduction

ISA Fieldbus is one of the famous digital protocols used in industrial control systems replacing legacy 4-20mA analog field wiring between controller and its sensors and actuators. It is become known starting from late 1996 as "Foundation Fieldbus" ([**1**] and [**2**]). Extensive studying for different variables and parameters of the Foundation Fieldbus protocol H1 (31.25 Kbps) and H2 (1 & 2.5 Mbps) lead to calculate average Fieldbus time delay that encounter any frame on the link ([**3**], [**4**] and [**5**].

Fieldbus technology is a subject of many recent researches. They can be classified in two main categories; first category covers the communication features, parameters and installation of Fieldbuses [**6**], [**7**] & [**8**]. Second category focuses on the industrial control features of Fieldbuses in networked control systems (NCS) [**9**], [**10**] and [**11**]. This work belongs to the second category. It is typically concerned with Foundation Fieldbus. It focuses on network delay and its effect on closed loop control systems. This paper adopts different pole placement control methods to face network delay effect.

The first assumption made in this paper is considering Foundation Fieldbus network as a digital filter with unity gain and only lag time delay ([**12**] and [**13**]). This assumption is made to focus only on Fieldbus time delay factor, while the effect of network attenuation and frame probability of error due to noise have been encapsulated in Fieldbus frame throughput [**14**]. The second assumption considers a simple closed loop system from one Fieldbus sensor (analog input function block), digital pole-placement controller and one Fieldbus actuator [**15**].The third important assumption is considering a case study of time critical process with very small dead time in the order of tenth seconds [**16**].

Paper proved that Fieldbus network delay is critical for process with even relatively small dead time. Simulation results show that network delay may result in unstable closed-loop performance if not considered by control design. The paper presents an acceptable performance with pole-placement control algorithm. This was unachievable by some classical control methods [**17**].

The paper is organized as follows: Section 2 declares Foundation Fieldbus parameters used in calculating network delay. Section 3 gives the plant model on which closed-loop control law is based. Section 4 describes pole-placement digital control algorithm. Section 5 contains simulation results which demonstrate the power of the proposed control design approach. Finally, paper ends up to conclusions in section 6.

2. Foundation Fieldbus Parameters

In case of control loops execution using Fieldbus network connecting controllers, sensors and actuators, the Fieldbus publisher –subscriber communication scheme is used. This Fieldbus scheme called "scheduled transmission" in which any field device can publish its data on Fieldbus network when receiving "**C**ompel **D**ata **D**ata **L**ink **P**rotocol **D**ata **U**nit" **(CD DLPDU)** from "**L**ink **A**ctive **S**cheduler" **(LAS)** Fieldbus master node [**15**].

In our case study, we considered Fieldbus frame called "**D**ata **D**ata **L**ink **P**rotocol **D**ata **U**nit" (**DT DLPDU)** which is consisting of **128** data bytes on the average [**4**]. Therefore it can handle up to **64** analog values for sensors and/or actuators assuming **16 bits** per each analog value. This means that we assumed high traffic of Fieldbus frames over network by including other nodes data (controllers, sensors and actuators) as well.

Paper assumed that length of Fieldbus network is one segment length equals **1900m** in case of Fieldbus H1. This means that worst-case network length is considered [**4**].

Foundation Fieldbus throughput **(1/Tv)** is defined as the inverse of average time between two successive transmissions of Fieldbus frames over noisy network.
Starting from parameters like frame transmission time **(Ti)** and frame throughput **(1/Tv)**, it is possible to calculate **time delay that one frame on the average** suffers over Fieldbus network. The calculated time delay in Table 1 includes delay due to several elements:

1. **AWGN** noise on Fieldbus network.
2. **Impulsive** noise on Fieldbus network.
3. **Propagation delay** on Fieldbus network.
4. **Processing delay** of Fieldbus network.
5. **Queuing delay** of Fieldbus network.

This is because the throughput calculations in Table 1 were based on above factors [**14**].

Table 1 below shows summarized Fieldbus network delay in different cases. Foundation Fieldbus H2 has relatively small delay. Fieldbus H1 category has more dominant influence with respect to the sampling time. Though, both cases affect the robustness of the closed-loop control. In this paper, we emphasize on the effect of Fieldbus H1 network delay while providing a possible tool to analyze jitter effects on closed-loop stability.

Table 1 Fieldbus time delay at fixed frame length (1208 bits).

Foundation Fieldbus	**H1 (31.25 Kbps)**	**H2 (1 Mbps)**	**H2 (2.5 Mbps)**
Ti=1208/R	0.038656	0.001208	0.0004832
1/Tv=γ	13.53	825.54	2068.63
$\mathbf{T_d=T_v-T_i}$	0.035255	3e-06	2.2e-07
$\mathbf{T_s=T_i}$ **sec.**	0.038655	0.001208	4.832e-04
$\mathbf{T_d/T_s}$ **%**	91 %	0.25 %	0.046 %

Where **R, Ti, 1/Tv, Td, and Ts** are the Fieldbus baud rate, the frame transmission time, the frame throughput, the delay time and the sampling time respectively.

3. Plant Model

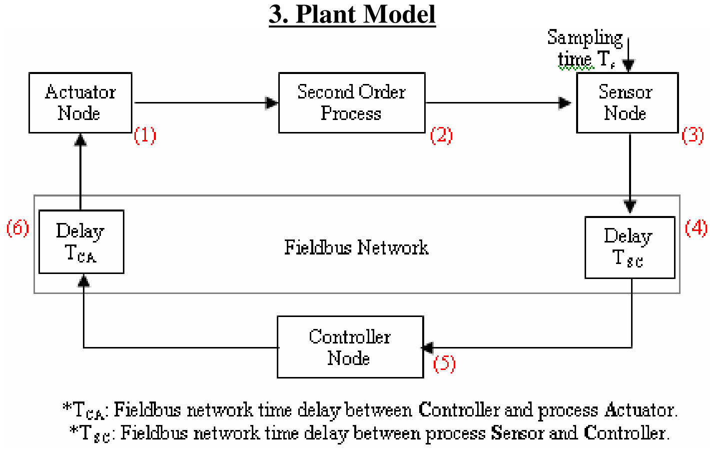

Figure 1 Closed loop control system via Fieldbus network.

Figure 1 represents a physical block diagram of a closed-loop system considering Fieldbus network delays. Process, sensor, and actuator are assumed to be lumped in a continuous first order transfer function given by:

$$G(s)=\frac{K}{(\tau s+1)} \qquad (1)$$

Where **K** and τ are the static gain and time constant. Though it is a simple process model, the control design method can be used for more complicated processes [**17**].

The plant model can be reshaped according to usage of RST pole-placement controller for tracking and regulation as below:

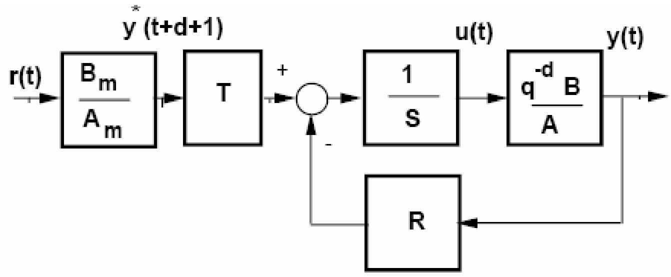

Figure 2 Pole-placement tracking and regulation control.

A generic discrete plant model is described, using the "q^{-1}" shift operator, as:

$$\mathbf{y(t)A(q^{-1}) = q^{-d-1}\,B(q^{-1})\,u(t)} \qquad (2)$$

where u(t) and y(t) are the lumped plant control input and output respectively and "d" is the dead time multiples of sampling period. The polynomials A(q-1) and B(q-1) are of order na and nb. The plant dead time should implicitly contain Fieldbus network delay.

Table 2 shows the different simulation models based on small variation of the sampling time. Notice that the main effect is on the "zeros" locations rather than the dead time multiples of the sampling period. This would reflect how network delay jitter would affect plant model. Closed-loop stability will be affected if these variations were not considered while designing the control algorithm.

Table 2 Simulation Model Parameters.

Foundation Fieldbus H1 Controlled Process Delay = 2.4Ts	$G(q^{-1})=\frac{q^{-3}(0.02293+0.01499\,q^{-1})}{(1-0.9621q^{-1})}$
Foundation Fieldbus H1 Controlled Process Delay = $2.6T_s$	$G(q^{-1})=\frac{q^{-3}(0.01534+0.02257q^{-1})}{(1-0.9621q^{-1})}$

Note that T_{CA} and T_{SC} are modeled as of equal values in Table 2.

The main difference between the two models is the location of the transfer function zero. When the delay has a fraction part less than half the sampling time, the zero is inside the unit circle and vice versa.

4. Pole-Placement Control

A canonical R-S-T pole-placement control for the above mentioned plant model is given by

$$\mathbf{S(q^{-1})u(t) = T(q^{-1})y^*(t+d+1)-R(q^{-1})\,y(t)} \qquad (3)$$

where

$$\mathbf{S(q^{-1}) = 1 + s_1\,q^{-1} + s_2\,q^{-2} + \dots\ s_{ns}\,q^{-ns},} \qquad (4)$$

$$\mathbf{R(q^{-1}) = r_o + r_1\,q^{-1} + \dots\ r_{nr}\,q^{-nr}} \qquad (5), \text{ and}$$

$$\mathbf{y^*(t+d+1) = [B_m(q^{-1})/A_m(q^{-1})]\ r(t)} \qquad (6)$$

Notice that [Bm(q-1)/Am(q-1)] is a desired reference model [**17**]. The set point r(t) is typically taken as a unit step. The resulting closed-loop transfer function, between the reference y*(t+d+1) and the plant output is given by

$$\mathbf{H_{cl} = [q^{-d-1}\,B(q^{-1})\,T(q^{-1})] / [A(q^{-1})\,S(q^{-1}) + q^{-d-1}\,B(q^{-1})R(q^{-1})]} \qquad (7)$$

$$\mathbf{= [q^{-d-1}\,B(q^{-1})\,T(q^{-1})] / P(q^{-1})} \qquad (8)$$

where

$$\mathbf{P(q^{-1}) = A(q^{-1})\,S(q^{-1}) + q^{-d-1}\,B(q^{-1})R(q^{-1})} \qquad (9)$$

is the characteristic equation known as "Diophantine or Bezout equation" [3]. Designing an R-S-T pole-placement controller implies calculating both the polynomials $S(q^{-1})$ and $R(q^{-1})$ in such a way that verifying the pre-given equation. In order to have a unique solution, $A(q^{-1})$ and $B(q^{-1})$ polynomials must have no common factors. Moreover we should guarantee:

$$\mathbf{np = deg\,P(q^{-1}) < na + nb + d - 1} \qquad (10),$$
$$\mathbf{ns = deg\,S(q^{-1}) < nb + d - 1,} \qquad (11) \text{ and}$$
$$\mathbf{nr = deg\,R(q^{-1}) < na - 1} \qquad (12)$$

The polynomial $P(q^{-1})$ specifies the regulation rejection dynamics. The polynomial $T(q^{-1})$ specifies the desired tracking trajectory. This trajectory is deformed due to non simplification of the zeroes lying outside the unit circle in the "z" transform domain. An integrator will be imposed in $S(q^{-1})$ to cancel the steady-state error.

5. Simulation Results

The aim of this simulation results is to tune and choose a suitable pole-placement controller that considers network delay. Simulation results will also show the effect of varying network delay on the closed-loop control performance. Matlab is used to resolve all Bezout equations encountered [18]. As a general approach, an integrator is implied in the "S" polynomial in order to have zero steady-state error. The closed-loop desired regulation and tracking dynamics are taken such that the damping ratios equal 0.1 and 0.8 while the natural frequency equals 1.5/Ts and 0.5/ Ts

Figure 3 shows both tracking and regulation closed-loop performance of the RST pole placement controller with the first delay model (2.4Ts). The zero is safely canceled while solving Bezout equation.

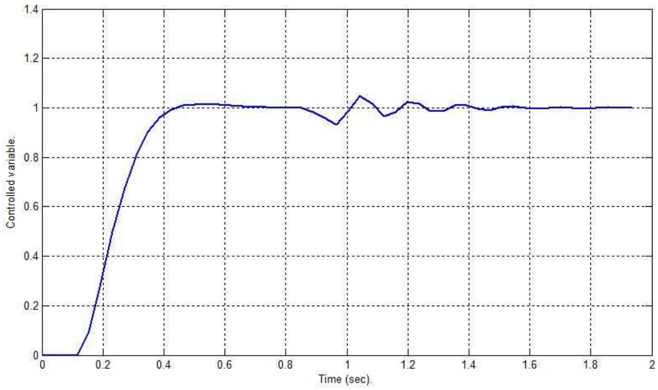

Figure 3 Pole-Placement Design (With Zero Cancellation).

Figure 4 Shows a similar closed-loop response for the second network delay model (2.6Ts). The difference should appear in the control signal. Another different control method that does not simplify the unstable zero, is used. Otherwise, unstable closed-loop response will happen.

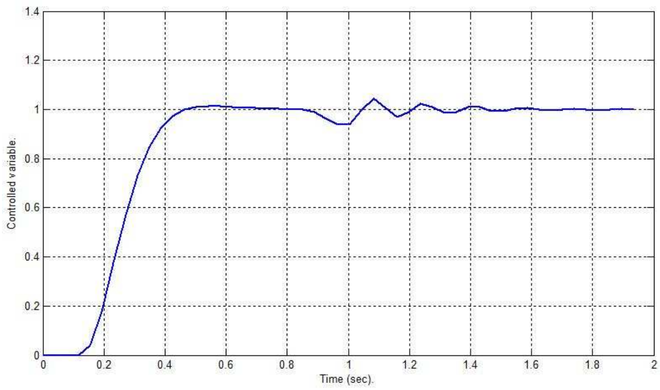

Figure 4 Pole-Placement Design (Without Zero Cancellation).

Finally a preliminary robustness simulation is done to study network delay jitter effect on closed-loop performance.

Figure 5 shows that even small variation results in unstable regulation response. Better performance could be obtained by slowing down the desired regulation dynamics. Future research will treat this problem by reshaping sensitivity function in order to avoid such undesirable response [17].

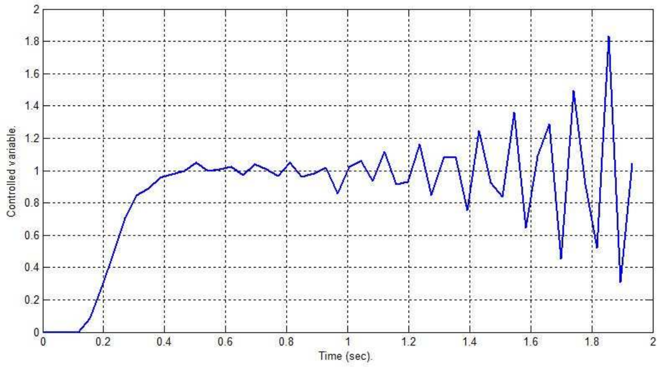

Figure 5 Robustness Against Network Delay Variation.

6. Conclusion

Pole-placement technique is used in closed-loop with a process that has foundation Fieldbus network delay effect. Zero cancellation results in instability with some values of this delay. Simulation results show, even without zero cancellation, instability when having small variations of network delay. Future work will focus on treating this problem by closed-loop sensitivity robustness analysis.

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