Adaptive Regulator for Networked Control Systems: MATLAB and True Time Implementation

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Abstract: Networked Control Systems (NCSs) employ digital network for transmitting control and monitoring information among system components. Control information over digital network may be delayed due to transmission and this can adversely affect the control performance. To achieve desired performance in the presence of delays the controller needs to modify its gains based on the channel delay. In this paper, we propose a simple adaptive regulator that uses the first order approximation for computing the controller gains based on prior knowledge of channel delays from experiments. Simulation results indicate that the adaptive regulator performs well even when we model the delay via Gaussian distribution. Delay samples obtained from MODBUS over TCP/IP and data-networks are used to illustrate the performance of the controller. The controller is implemented in True Time to illustrate its real-time performance.

Key Words: Networked Control Systems (NCSs), adaptive control, random delays, linear quadratic regulator (LQR), Adaptive regulator (AR)

1 INTRODUCTION

Digital communication channels have proliferated industrial control loops and are being used for transmitting control and monitoring information. Control loops that employ digital network for transmitting control data are called networked control systems (NCSs). A detailed overview of NCSs can be found in [1]-[5], see also the references therein. Time-varying delays are introduced in the transmitted data due to the digital communication links and these delays deteriorate the system performance, eventually leading to instability. Most results in NCSs are motivated in designing stabilizing controller, considering the worst-case de-stabilizing effect of delays. This design is a bit conservative as controller parameters are computed based on the worst-case conditions. Traditionally, adaptive controllers have been used in scenarios wherein control systems encounter time-varying parameters. The role of adaptation in NCSs has not yet been fully explored and this is mainly due to two reasons, namely: *(i)* the need for prior knowledge of delays, and *(ii)* computation delays induced in controller nodes due to on-line computations. Our goal is to propose computationally effective adaptive controller.

Adaptive control of NCSs is a recent research topic and the available results can be classified into three broad categories: *(i)* gain-scheduling based approaches [7, 10, 11, 12], *(ii)* adaptive controllers based either on some assumptions regarding the delay or delay models [6, 8, 13], and *(iii)* adaptive control rules that employ parameter identification followed by an controller update [14, 15, 9]. Most of the results, except [14, 13], do not consider explicit performance metrics intended from the closed-loop systems. Adaptive control rule that computes the controller gains using channel information and a model that captures the required performance from the plant has been proposed in [14]. The adaptation rule proposed in [14] requires delay measurements and complex matrix computations that induce undesirable computation delays. In this investigation, we propose a linear adaptive regulator that is based on the quadratic cost function (LQR), and an approximation scheme that simplifies the computation of the controller gains. Resulting adaptive controller is simple and requires only an approximate knowledge of channel delays to meet the performance specifications. In our analysis, we use for that purpose an empirical Gaussian model based on the experiments conducted on MODBUS over TCP/IP network. The adaptive control rule is implemented in True Time toolbox to show the performance of the adaptive controller.

The remaining part of the paper is organized as follows, In section II, we present the NCSs model and formulate the problem. In section III, we propose the adaptive regulator design, and present the empirical model for time-varying delay obtained from the experiments conducted on MODBUS over TCP/IP and industrial controller AC-500. Simulations in True Time are shown to illustrate the proposed adaptive controller in section IV. Conclusions and future directions of this investigation are discussed in section V.

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2 Problem Statement

Consider the linear time-invariant (LTI) system

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu^*(t) \\ y(t) &= Cx(t) \end{aligned} \tag{1}$$

with controller

$$u^*(t) = u_k, \qquad t \in [kh + \tau_k, (k+1)h + \tau_{k+1}) \tag{2}$$

where $x(t) \in \Re^n$, $u^*(t) \in \Re^m$, $y(t) \in \Re^p$ are the state, input and output vectors respectively and A, B, C are constant matrices with appropriate dimensions. Networks N_1 and N_2 are used to connect sensor and controller output to the controller and plant respectively. Generic NCS with dynamics (1) and (2) is shown in Fig. 1. Total delay in

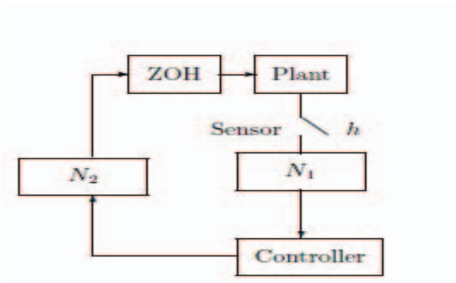

Figure 1: Networked Control System (NCS)

the control input τ_k is the sum of networked-induced delays in the channels N_1 and N_2, denoted by τ_{sc} and τ_{ca}, respectively and computation delay τ_c in the controller

$$\tau_k = \tau_{sc} + \tau_c + \tau_{ca} \quad for \;\; k = 0, 1, 2, 3, ... \tag{3}$$

There exists lot of theory for time-delay systems, but often the papers in the field only cover systems with fixed though possibly unknown delays. In our paper, the delays are assumed to be time-varying and bounded but otherwise changing randomly. This is the typical situation in a NCS [2]. We do not assume that the probability distribution of total delay τ_k is known but find the empirical distributions using experiments conducted on real-time network. In general, we are interested in analyzing the NCSs where the total delay τ_k is less than the sampling period h and drop the data with delays greater than h, i.e. when $\tau_k > h$. These assumptions ensure that the most recent feedback information is available at the controller and out-of-sequence samples are not delivered. Sampling the system (1) under these assumptions leads to the discrete-time model as in [17, 18]:

$$\begin{aligned} x_{k+1} &= \phi x_k + \Gamma_0(\tau_k)u_k + \Gamma_1(\tau_k)u_{k-1} \\ y_k &= Cx_k \end{aligned} \tag{4}$$

where $\phi = e^{Ah}$, $\Gamma_0(\tau_k) = \int_0^{h-\tau_k} e^{A\lambda}\, B\, d\lambda$ and $\Gamma_1(\tau_k) = \int_{h-\tau_k}^{h} e^{A\lambda}\, B\, d\lambda$.
The problem is to design an adaptive controller that adapts its gains based on the delays τ_k to regulate the state with minimum control effort and/or to meet the desired performance in the presence of time-varying delays. In particular, the controller should

1. reduce the deviations of the state x_k from the reference signal r_k with minimum control effort
2. reduce the computation delay

Further, the performance of the adaptive control scheme needs to be tested in a real-time scenario. In order to accomplish this, we employ the True Time package with Simulink to illustrate the effectiveness of the proposed adaptive control scheme. One may verify that there are conflicting controller design requirements and this makes control design complex.

3 Adaptive Controller Design

In this section, an adaptive control scheme called the adaptive regulator is proposed. This regulator adapts its gain depending on the time-varying network delays.

3.1 Adaptive Regulator Design

The control objective is to achieve good regulation with minimum control effort based on the LQR approach using the cost function

$$J = \sum_{\tau=0}^{N} (e_\tau^T Q e_\tau + u_\tau^T R u_\tau) + e_N^T Q_N e_N \tag{5}$$

In (5), $e_k = x_k - r_k$, $Q \geq 0$ and $R > 0$ are weighing matrices of appropriate dimensions, and $Q_N \geq 0$ is the terminal weighing matrix.
Define the cost-to-go function at time instant k is,

$$\begin{aligned} J_k(x_k) = \min_{u_k,\dots u_{N-1}} \sum_{\tau=k}^{N-1} (e_\tau^T Q e_\tau + u_\tau^T R u_\tau) \\ + e_N^T Q_N e_N \end{aligned} \tag{6}$$

subject to relations(4)
Note that $J_k(x_k)$ gives the minimum of LQR cost-to-go, starting from the state x_k at time instant k. It has been shown that $J_k(x_k)$ is quadratic, $J_k(x_k) = x_k P_k x_k + 2q_k x_k + r_k^T Q r_k$, where $q_k = -Q^T r_k$, $P_k = P_k^T \geq 0$ that can be found recursively working backwards from $k = N$ by taking $P_N = Q_N$.
Now according to the dynamic programming principle, suppose we know $J_{k+1}(x_{k+1})$ and look for optimal u_k. Observe that u_k affects the terms $u_k^T R u_k$ and $J_{k+1}(x_{k+1})$. Therefore,

$$J_k(x_k) = \min_{u_k} [(x_k - r_k)^T Q (x_k - r_k) + u_k^T R u_k + J_{k+1}(x_{k+1})] \tag{7}$$

From the necessary condition for optimality, we obtain, taking into account (4),

$$Ru_k + \Gamma_0^T P_{k+1}[\phi x_k + \Gamma_0 u_k + \Gamma_1 u_{k-1}] + \Gamma_0^T P_{k+1} r_k = 0 \tag{8}$$

As $N \to \infty$, the value of P_{k+1} approaches a steady value and can be replaced by a constant matrix $P \geq 0$. This simplification, with little manipulation leads to

$$u_k = L_x(\tau_k)x_k + L_u(\tau_k)u_{k-1} + L_r(\tau_k)r_k \tag{9}$$

where

$$
\begin{aligned}
L_x(\tau_k) &= -(R+\Gamma_0^T P\Gamma_0)^{-1}\Gamma_0^T P\phi \qquad (10)\\
L_u(\tau_k) &= -(R+\Gamma_0^T P\Gamma_0)^{-1}\Gamma_0^T P\Gamma_1\\
L_r(\tau_k) &= -(R+\Gamma_0^T P\Gamma_0)^{-1}(-\Gamma_0^T Q^T)
\end{aligned}
$$

are the adaptive control gains that depend on the network delay τ_k [29]. Obviously, the control rule (9) requires the

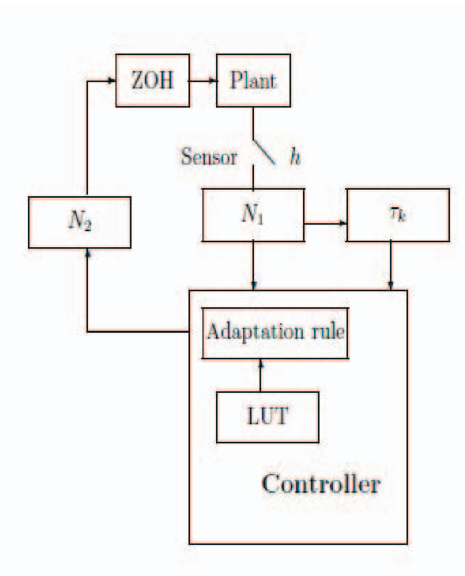

Figure 2: Schematic Block Diagram of Adaptive Regulator

knowledge of the delay τ_k to compute Γ_0 and Γ_1. Moreover, computational complexity increases as the system order n increases. Below we suggest how to overcome these shortcomings.

3.2 Modeling Time-Varying Delays

Modeling time-varying delays in communication channels has been investigated in [22, 23, 24, 8, 25, 26]. Delays in communication channels can be modeled using empirical distributions [22, 23, 24], Markov Chain [25], shifted Rayleigh model [8] and Markov Chain Monte Carlo (MCMC) techniques [26]. Usually in industrial automation network used in sensor to controller and controller to actuator channel are correlated meaning that the delays τ_{sc} and τ_{ca} are related by

$$\tau_{sc} = \xi \times \tau_{ca} \qquad (11)$$

where ξ is an arbitrary constant determined from experiments. We use measurements from experiment on Modbus over TCP/IP to model the delay. The samples generated by the Gaussian distribution are shown to be close enough to capture the delay distribution and will be used in controller design instead of actual measurements. In case when empirical distribution does not fit the normal distribution well enough, the MH-sampler proposed in [26] can be used for computation of delays.

3.3 Approximation of AR Gains

To simplify the computation of the controller gains (10), a look-up-table based approach was used in [26]. Unfortunately, then the controller induces chattering behavior in output and moreover, there are no guidelines to fix the number of controllers in the table that, in general, depends on the delays in the channel.
In this paper, we propose the first order approximation for the controller gain

$$L(\tau_k) \approx L(\tau_0) + \frac{\partial L}{\partial \tau}(\tau_k - \tau_0) \qquad (12)$$

that will be improved later by introducing a learning parameter $\Psi(\tau)$, computed from the off-line simulation, yielding

$$L(\tau_k) \approx \Psi(\tau)\; L(\tau_0) + \frac{\partial L}{\partial \tau}(\tau_k - \tau_0) \qquad (13)$$

Note that in (12) and (13) τ_0 is the nominal delay or the gain, corresponding to the sampling period h of the system.

4 Results and Discussions

This section presents the results of this paper which is an extension to the previous work of the authors [29] on adaptive control of NCSs. In [29] results for the adaptive control rule has been implemented using MATLAB, whereas the result presented in this section have been implemented with True Time package. This modification is useful in verifying the real-time behavior of the NCSs with the adaptation rule. The results obtained from MATLAB have been included in this section to increase the clarity about the performance of the adaptive control rule.

4.1 Numerical Example

The double integrator system

$$\dot{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u(t) \qquad (14)$$

$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x(t)$$

is used to illustrate the effectiveness of the proposed adaptive regulator. Discretization of (14) with sampling period h and assuming delays in the channel $\tau_k \leq h$ leads to

$$x_{k+1} = \begin{bmatrix} 1 & h \\ 0 & 1 \end{bmatrix} x_k + \begin{bmatrix} \tau(h-\frac{\tau}{2}) \\ \tau \end{bmatrix} u_{k-1} + \begin{bmatrix} \frac{(h-\tau)^2}{2} \\ h-\tau \end{bmatrix} u_k \qquad (15)$$

In simulation, we first employ MATLAB with Gaussian

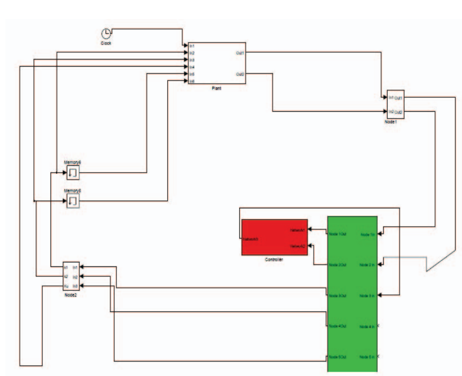

Figure 3: True Time simulation of Adaptive Regulator

model for the channel delay. Second, we simulate the controller in True Time and introduce the delay sample, obtained from the Gaussian distribution during the execution. Here network loading (presence of additional nodes) is considered for modeling the delays. In both cases, the controller uses the approximation (13) to compute the gains.

4.2 MATLAB simulation

The sampled-data representation of NCS with total delays less than sampling time can be obtained using MATLAB together with the routine *NCSsd*, developed by the author of this paper [27]. Delay measurements (assuming symmetrical channels) are used to model the Gaussian distribution with mean and variance computed from the experiment. The states of the adaptive regulator for $h = 10\ ms$ and with delay having mean of 30 ms and variance of 10 ms are shown in Fig. 4. This response is obtained considering loading in the channel. The response of the adaptive regulator h=10 ms and with a delay having mean 6 ms and variance of 1.5 ms is shown in Fig. 5. The regulatory performance of the AR controller can be ascertained from these results. Further, the controller works well even with empirical model for delays with a first order approximation that significantly simplifies the design.

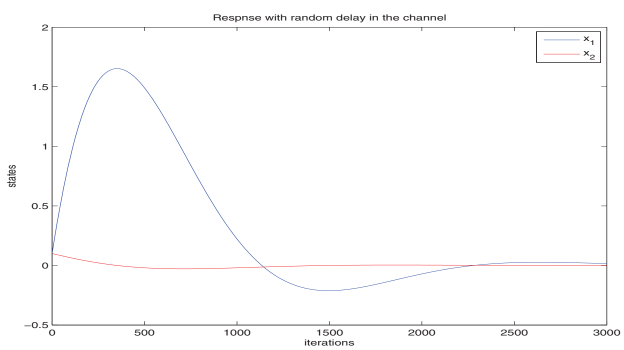

Figure 4: States of the double integrator system with network loading using MATLAB simulation

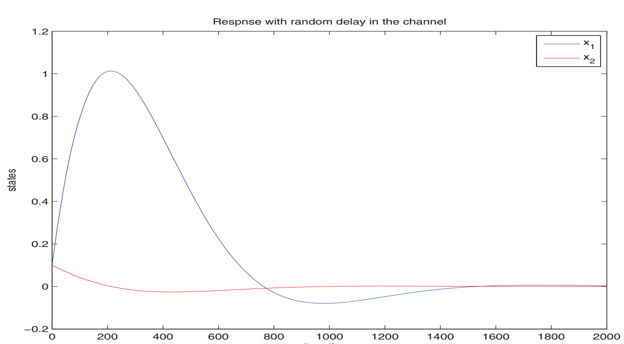

Figure 5: States of the double integrator system without network loading using MATLAB simulation

4.3 True Time simulation

To mimic the real-time control scenario, we use the True Time toolbox [30] to implement the adaptive regulator. Its implementation in Simulink is as shown in Fig. 3. The network and the controller node are created using True Time and embedded MATLAB function NCSsd is used for implementing the sampled data model (15). States of the sampled-data double-integrator system (15) employing Modbus over TCP/IP communication channels for information exchange with AR are shown in Fig. 6. The channel delay changes after 2000 iterations. The iterations can be converted into the time by considering the controller hardware to which the AR algorithm is ported. The variations in the state feedback gains are shown in Fig. 7.

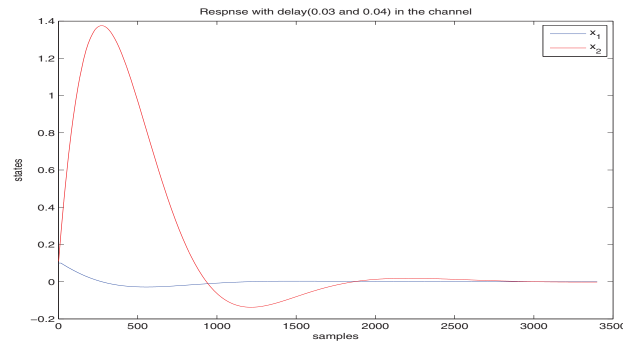

Figure 6: State values of the double integrator system with network loading using True Time simulation

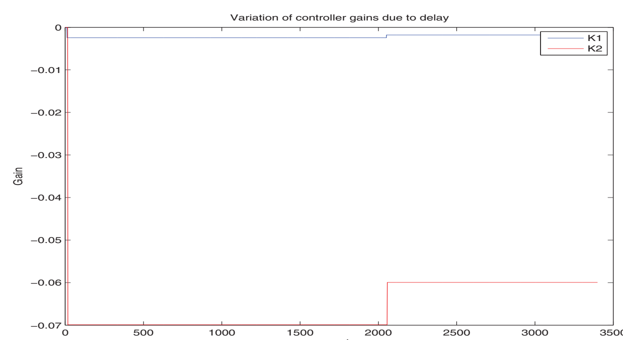

Figure 7: Variations in controller gains in True Time simulation

4.4 Summary of Results

Simulation using MATLAB and True Time indicate good regulatory performance of the adaptive regulator. The adaptive regulator only requires the knowledge of delays in the form of Gaussian distribution for computing the controller gains. Further, the approximation used for computing the controller gains is very simple and eliminates the need of matrix computations required by the other adaptive controllers proposed in the literature, such as those in [14, 15, 9].

5 CONCLUSIONS

In this investigation, a simple adaptive regulator for NCSs subjected to random communication delays has been proposed. The controller only requires the knowledge of the delay as an empirical Gaussian dsitribution (obtained from experiments) and matrix computations are not required for computing the controller gains. Effectiveness of the proposed scheme is illustrated using True time and MATLAB based simulation. Stability analysis and packet loss handling are left for the future studies.

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