NETWORKED CONTROL SYSTEMS: RANDOM DELAY COMPENSATION WITH PLAY-BACK BUFFERS AND SMITH PREDICTOR

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Abstract

The benefits brought by network communication in the context of closed loop control stimulated a great research focus on the networked control systems (NCS). Multiple solutions and theories were emitted and proposed throughout the time aiming for eliminating the drawbacks brought by the specific network characteristics such as variable time delay and packet loss. We propose herein a combination between play-back buffers, which eliminate the randomness of the network delay, and a Smith predictor which will compensate the resulting process time delay. The performances of the proposed control system will be compared with those obtained by using an unbuffered PID controller.

1. Introduction

The use of network communication in a control loop brings indisputable benefits such as cost reduction, flexible structure and applications. These advantages are shadowed by the serious challenges brought-in by the network-induced delay effect in the control loop. Random access local area networks (CAN and Ethernet) bring-in the problem of waiting time delays due to queuing and frame collision [1]. The presence of a network brings constraints in the design of the control system, as information between the various decision makers must be exchanged according to the rules and dynamics of the network [2].

Network communication is done via data frames which encapsulate the control signal sent to the considered plant. The system will respond by sending the sensor measurement to the controller [3], [4].

The constant delays methodologies fail since network delays are time-varying. Network delays can have several sources: system components waiting for network availability, the placement of the frame on the network, the propagation of the frame.

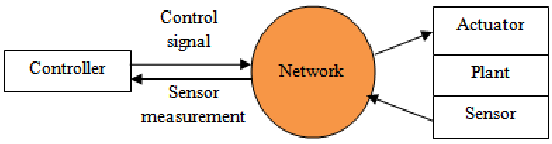

Figure 1. Structure of a NCS.

Higher layer network protocols (TCP) may require retransmission if a packet contains an error. Therefore, when one or more packets are lost, the transmitter retransmits the lost packets. However, since a retransmitted packet usually has a long delay, the retransmitted control packets are outdated by the time they arrive at the actuator [5].

Random network delays were modelled in different manners such as: Poisson technique or even using Markov chains. Also many recent control methodologies were issued in order to maintain the stability of the system.

One of the most popular solutions is the queuing mechanism used to eliminate the random character of the delays. Luck and Ray used an observer to estimate the plant state and a predictor to compute the predictive control based on past measurements [6].

Chan and Ozguner developed the probabilistic predictor-based delay compensation methodology using probabilistic information along with the number of packets in a queue to improve state prediction [7].

Hong developed the sampling time scheduling methodology to appropriately select a sampling period for a NCS such that network delays do not significantly affect the control system performance, and the NCS remains stable [8]. This methodology is originally used for multiple NCS on a periodic delay network, in which all connections of every NCS on the network are known in advance.

Nilsson proposed the optimal stochastic control methodology to control a NCS on random delay networks, treating the effects of random delays as a Linear–Quadratic–Gaussian (LQG) problem [4]. Off course, each of these strategies, along with the fuzzy approaches or the event-based methodologies, has its own benefits and drawbacks, depending also on additional concern factors such as: linear or non-linear plant, cyclic or random service network, bounded or unbounded delay and so on [9]. We will choose to consider further on and analyze a particular queuing strategy. The purpose of this implementation is to eliminate the random character of the network delays and make the variable time delay more accessible and controllable. This implementation will then be combined with a Smith predictor, a predictive controller known for its simplicity and for the good results provided by eliminating the delay from the control loop.

The performances obtained with this buffered controller will be compared with the results obtained when using an unbuffered PI controller, subject to variable time delays. We also try to pull conclusions and raise questions regarding the sampling time, the choosing of the play-back time and the delay generation.

2. **Preconditions And Objectives**

In all our considerations, we will try to keep as close as possible to the real behaviour of a network communication.

Simulink was used in order to simulate the networked control system and not other network simulation tools, as it is desired to have full access and control over the behaviour of the system. A first order plant and a constant sampling time will be used.

It is known that delays have a great influence over the system performances. As it can be observed in Figure 2, a PI controller can poorly manage the delays as their values grow.

These performances are obtained while constant delays were inserted between the PI controller and the plant and also on the feedback signal. It can be observed that at some point, while increasing the value of the delay, the stability of the system is compromised.

The Smith predictor's sensitivity to these changes in delay leads to prohibitively poor performance.

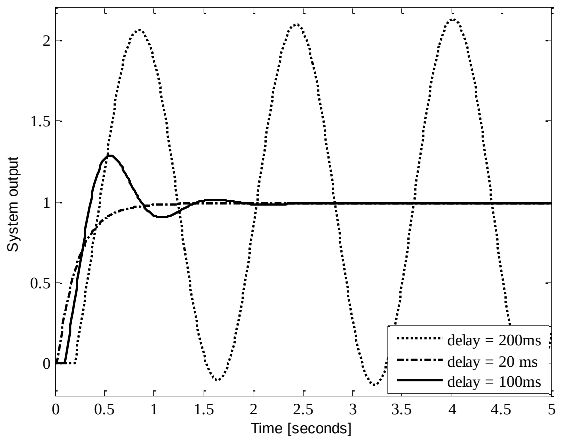

Figure 2. PI control: delays degrading the system performances.

Nevertheless, a lot of solutions and controller adaptations can robustly deal with constant delays. The Smith predictor is a well-known model predictive control method designed to take advantage of plant model and delay model information to effectively remove the delay from the control loop. As the purpose of this paper is to emphasis the usage of play-back buffers in the context of NCS, we will only present the block diagram used for the Smith predictor (Figure 3).

But we have not yet reached the point where we afford to discuss constant delays, as the random access area networks, have variable delays caused by queuing and packet loss [10].

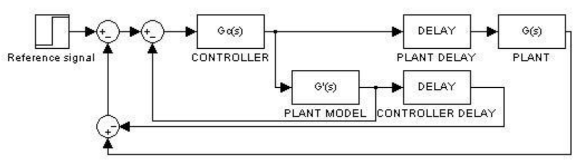

Figure 3. Block diagram of the Smith Predictor.

In general, we divide controllers for systems with time varying loop delays into two categories: buffered and unbuffered. A buffered controller can take advantage of a more deterministic delay but it has the drawback that it effectively increases the loop delay due to the play-back buffer. An unbuffered controller applies the control signal as soon as it is received. The PID controller can be implemented effectively without buffering because its derivative part serves as a crude predictor that is sufficiently robust to the time varying nature of the delay [11]. Intuitively, we know that the PID controller can manage well small delays but for longer delays, the gains of the PID controller become conservative and performance is significantly degraded [12].

We will try to compare bought situations and analyse the advantages and drawbacks.

3. Materials and Methods

In a real NCS, a detailed network analysis should be performed before operation. This will provide a realistic image over the network behaviour and consequently, over the delay distribution.

Generally, the delay in a NCS loop has three components: the delay from sensor to controller, the delay for the controller's calculations, and the delay from the controller to the actuator. All three components will be combined into one loop delay τ [13].

For simulation purposes, the network will be represented by a variable transport delay block supplied by a random number generator which will provide delay values (τ) in the range of 0 to 80 milliseconds (Figure 4).

Liberatore proposed a NCS variable time delay solution by introducing the play-back buffer designed to hold the control signal and to apply it only after a certain time range has pasted [12]. This strategy will be used in order to reach the point where we can freely apply the Smith predictor for constant delays. This method will eliminate the random character of the delay, transforming an unstable system with unexpected behaviour into a system able to assure acceptable performances. Clearly, adding any delay to a closed-loop system generally degrades performance. Consequently, this paper focuses on the analysis of the play-back buffers and on the basic idea of removing uncertainty in the delay – we do not aim necessarily for high control performances.

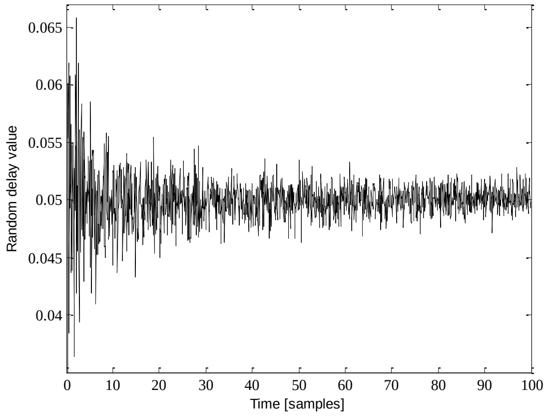

Figure 4. Random delay buffer.

Our simulation uses such a first–in/first-out (FIFO) queue which has the role of taking in the data packets, as they arrive and push them at a fixed time interval, called here the play-back time.

The functioning of this block is very simple and helps us simulate all the network effects. The transit packages will be pushed into the queue when a push signal triggers this operation and will be popped later on, in a FIFO order, when the pop signal triggers this operation. It is already clear that the design of the push and pop signals is essential; moreover, the manner in which the play-back time is chosen is crucial. The capacity of the buffer and the design of the pop signal give more flexibility in choosing the play-back time, but for safety and for eliminating any uncertainties the play-back time is usually considered as being equal to the maximum value of the delay. Regarding all these considerations and the adopted random delay buffer, the push and pop signals are configured as depicted in Figure 5.

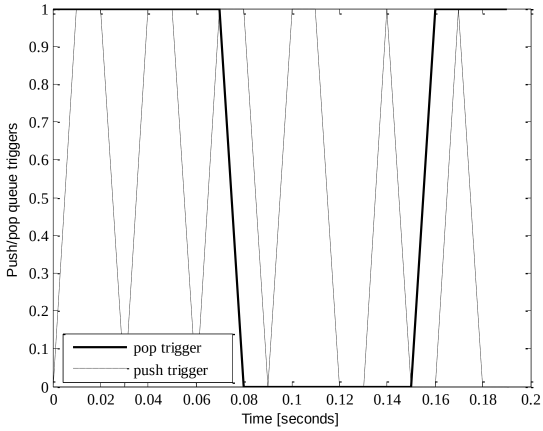

Figure 5. Push and pop signal levels.

As the queue block interprets the triggers as being either a rising edge or falling edge, Figure 5 basically presents that the push will be executed as soon as a control signal is available and it will trigger the storage of the packet onto the queue. As the play-back time is equal to the maximum value of the delay and rounded to the next sample time value, the signals will be pushed out of the queue later on, in this case at a constant rate of 60 milliseconds for a sample rate of 10 milliseconds. This means that the pop of the first packet will occur when the queue will already contain five packets. It is already clear that the additional delay introduced by the queue will negatively influence the system performances even if it gives control over the random character of the delay. This aspect is still discussed as it can be adjusted and controlled by means of variable sample times or other play-back time minimisation strategies.

The constant pushing rate creates the constant time delay which affords us to further apply the Smith predictor – this is the main contribution of the delay buffers.

Another important network characteristic which influences the loop control performances is the fact that the arrival of the frames will not necessarily respect their sending order. If two packages are sent one after another by the controller towards the plant, this does not necessarily mean that the first sent will be the first received by the process. Figure 6 depicts how, depending on our delay buffer, packet number 1 will arrive to the plant after 60 milliseconds, while packet number 2, which was sent after packet number 1, will arrive after 30 milliseconds.

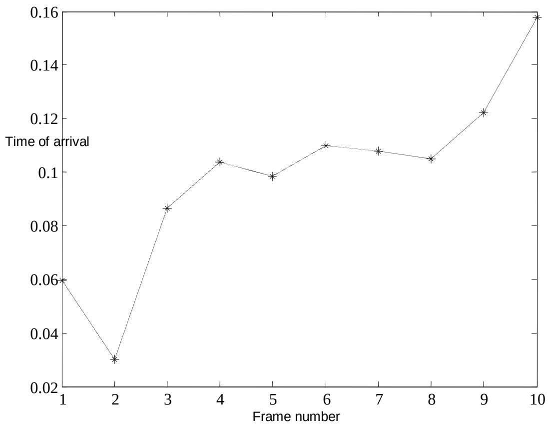

Figure 6. Out-of-order packets.

The same situation happens for packet 4 which arrives after packet number 5 and so on.In our simulation, as we have not considered yet a reordering mechanism, we will use these special "out-of-order" frames to simulate another network issue, that is, the loss of packets. Packet drops can be easily simulated by avoiding the pushing onto the queue of the out-of-order packets. This approach implies again that, in order for all these conditions to be accomplished, the delay buffer should be subject of a detailed offline pre-analysis. In real NCS, this analysis should consist of a long and responsible study of the network environment

4. Results And Discussions

Figure 7 shows the results obtained when using a PID controller and the proposed buffered controller.

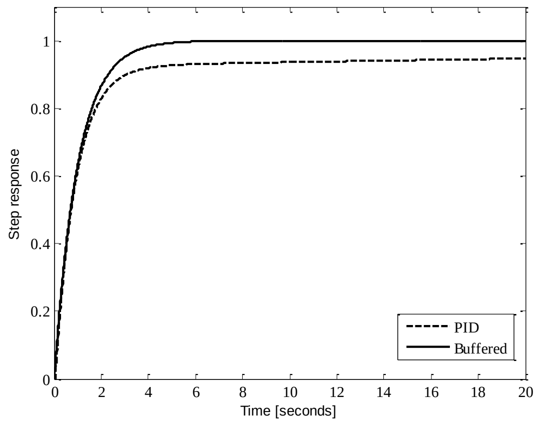

Figure 7. PID controller versus buffered controller, play-back time = the sample time, reference = 1.

The play-back time is equal to the sample time (10ms). This case is the ideal one but also problematic: if the play-back time equals the sample time, and the pushing of the packets is done as they arrive, there is a high possibility to have no available packets in the queue when the pop operation is triggered, at every sample, in this case. This situation should be usually avoided, by choosing the play-back time in such a manner so that at any pop action at least a packet would be available in the queue.

Anyhow, it is clear that, depending on the network delay behaviour, the play-back time is desirable to be as small as possible, this assuring that the resulting constant delay will be as small as possible. As depicted by Figure 7 the PID controller can handle the proposed variable time delay in a manner that does not destabilize the system but with relatively poor performances. The rising time is comparable with the results of the buffered controller which is quite performing, knowing that our buffered controlller will never be faster than this. This PI controller is designed to be conservative, in order to keep the system stable but in the same time it cannot assure a fast response and not even a zero stationary error. A more aggressive PID controller can be designed but with oscillatory or destabilizing effects.

We already know that the performances presented in Figure 7 are the best we can get with the current set up. Let us now observe in which way the play-back time influences the performances of the system.

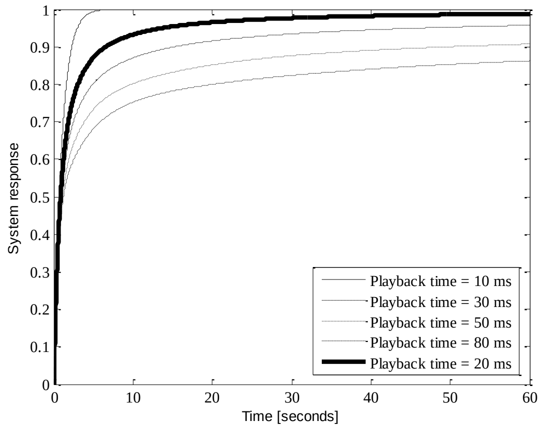

Figure 8. Performance degradation due to the increase of the play-back time.

Let us state again the preconditions of our simulation: first, we considered a fixed sample time of 10 milliseconds, we have omitted the out of order packets, transformed the variable time delay into a constant delay depending on the play-back time and used a Smith predictor to compensate the resulting delay. While all of these simulation elements can be modified or improved, we state that the most important factor is by far the play-back time. The case which assures the best performance is the one in which the play-back time is equal to the sample time. This means that a pop operation will be performed at every sample, so the play-back time has the smallest value possible. In order to get good results, this case has to be supported by a "pop empty queue" strategy. In our case, if the play-back time is set to 20 milliseconds, the queue will never be empty while a pop operation occurs.

Off course, it depends on the implementtation preferences or on the application flexibility if it is more desirable to implement a "pop empty queue" strategy and keep the play-back time to a minimum value with the additional risks (distortion of the control signal) or to perform an analysis over the delay buffer and queue behaviour and decide on a minimum play-back value which assures a safe queue transfer rate.

In real NCSs it is almost impossible to have this sort of accuracy and the safest solution remains the one in which the play-back time holds the maximum value of the delay range. In our simulation case, this value is 80 milliseconds which would not be that bad in a real situation. Off course this supposition depends a lot on the type of the controlled plant as wheal.

Anyhow, it is clear that with our buffered controller, the performances decline considerably with the increase of the play-back time. The best scenario (play-back time equals sample time) assures a comparable rise time with the PI controller but providing much better performances. As the play-back time increases, the controller is not able anymore to reach the reference and has a very slow growing trend. In the worst case scenario (play-back time equals 80 ms), the output barely reaches 0.8 in about 30 seconds and ends up at 0.9 after almost 100 seconds.

It can be concluded that in our case the most convenient solution is the situation in which the play-back time equals 20 ms. This case excludes the empty queue problems and gives acceptable performances, but as stated above, this implies an additional analyse of the queue behaviour in relation with the push/pop triggers. This case also assures better results than the PID controller and another general advantage is that by means of the queue block, the buffered solution gives much more manipulation and analyses possibilities of the random delay.

5. **Conclusions**

Regardless of the structure or network used, the system performances of NCSs will degrade due to the existence of network delays in the control loop. These delays are hard to handle because there is no existing criterion to guarantee or assure the stability of a NCS. Because of that, creating a network protocol-based application needs a lot of awareness regarding the feasibility and the reliability which can be provided by the selected control methodology.

This paper treated a networked control problem, using a simulated control system in order to emphasize the occurring network difficulties. By all means, we tried to stay as close as possible to the real case of network communication. We specifically focused on the use of play-back buffers to eliminate the variability in the loop delay. The value of removing all uncertainty in the loop delay was studied and the results with the performances of an unbuffered PID controller were compared. It is clear that PID controller cannot have full control over the network specific random delays.

The methodologies to control a NCS have to maintain the stability of the system in addition to controlling and maintaining the system performance as much as possible.

The buffered solution gives at first full control over all network specific characteristics such as packet loss or delay randomness. The queue block transforms all the problematic network aspects in familiar, classic control elements and affords in this way the usage of classical control strategies.

We have concluded that the play-back time has crucial influences over the system performances and that several strategies can be applied in choosing this parameter, depicting the compromise between good performance and accuracy and safety.

Off course the discussion remains opened over the manner of choosing the play-back time or the random delay analysis. Consequently, future work should consider more aspects of design of the controller and the play-back buffer such as: including the integration of variable sampling times, adaptive play-back delays, more complete analysis of the randomness in the delay.

6. Acknowledgements

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