U.P.B. Sci. Bull., Series C, Vol. 73, Iss. 2, 2011 ISSN 1454-234x

CONTROL SOLUTION FOR PROCESSES WITH TIME DELAYED COMMUNICATION COMPONENTS

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În acest articol se încearcă un studiu de caz realist asupra utilizării sistemelor de transmisie moderne şi componentelor automate de transmisie în zona controlului automat. Transmisia datelor cu ajutorul tehnologiilor fără fir au devenit universale în servicii destinate utilizatorilor finali. Preţul scăzut şi fiabilitatea lor fac din acestea o bună alegere pentru controlul automat. Trebuie însă ca soluţia oferită să trateze particularităţile metodei de transmisie: întârzieri, controlul diferit al stream-ului de date etc.

In this article is being described a realistic approach over utilizing modern data transmission systems and automatic transmission components in automatic control. Data transmission over wireless channels has become ubiquitous in end-user services. Low price and reliability are arguments for using this technology in automatic control. The solution yet must take into account the particularities of the method: time delay, different data stream control etc.

Keywords: automatic control, wireless, time delay, supervision, network

1. Introduction

The Internet has become a driver for new data transmission technologies. Wireless data transmission has become popular in home-use, and is becoming increasingly popular in different public services. Thus, being so popular, the cost has dropped and the quality of the service has increased.

In industrial data transmission, the focus is towards reliability and stability, more than on price. This is why wireless technologies are not used so much. To be able to implement such technologies, thus leading to dropping costs, one needs to evaluate all the issues that might affect the solution and to solve them. Thus the way to improvement requires studying needs, evaluating issues and researching for solutions.

The main tendencies today in industrial communication are the increase of the distance without increase of costs or degradation of the communication

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channel, the lowering of the costs of the devices that facilitate communication and the robustness of the solution. Clearly, these tendencies are normal, and they can be satisfied with the latest wireless technologies: mobile communication systems (for mobile phones) or wireless 802.11 or Bluetooth communication protocols. The significant increase of the distance over which the data is transmitted without the significant increase of the cost is the main argument in favour of these technologies. The standardization and wide usage of these communication channels lower the cost of the devices which are used. Furthermore, the wide usage of these channels has proven their technological robustness.

The introduction of wireless data channels in automated systems is not as trivial as it should be, though. This is caused mainly by the lack of the industrial application layer to facilitate the implementation of these automated systems. And this is partly due to the lack of a protocol fit for industrial communication over this kind of channel, and partly due to the lack of control algorithms adapted to these data transmission channels and these protocols.

2. TCP communication

There is proof that standardization is the key to lower costs and increase robustness of one product, but this tends to lower the rate of introduction of new technologies. If the Internet offers the cheapest means of transmitting data over physically wired areas, and also the high standardization, the costs and robustness of an automated system using Internet as data bearer are satisfactory. But this still leaves out some cases where in distributed systems wiring is too expensive or simply impossible (e.g. systems distributed over remote areas). Therefore introducing wireless communication over Internet can prove very efficient in terms of costs, robustness and performance [2].

The Internet is based on TCP/IP protocol, which is by far one of the most well known standards in communication, being robust and cost-efficient. Using TCP over a small cable network or a large network with optic fiber poses no bandwidth problems. Even if the dynamic of the system is high, the bandwidth is large enough to transmit data in real-time with no or few delays. These delays can be modeled as a stochastic model [10] and managed accordingly. This method, however, treats the transmission channel as an ideal channel with perturbations, and tries to eliminate them, the channel itself being a system with parameters. When implementing a control system, the transmission channel's model is introduced in the model of the process, being treated as part of the process itself. This method works very well as long as the transmission channel has an insignificant model in comparison to the process itself. But if the channel presumably introduces a time-delay which is larger than the process' time constants, the control system try to control the process with the transmission channel as well. As a result, a big part of the effort of the algorithm of control is consumed while eliminating the perturbations introduced by the communication channel. And TCP used over a wireless communication channel can introduce further problems, as described in [8].

2.1 TCP in Wireless Data Transmission

The Transmission Control Protocol (TCP) was developed for data connection through wired networks and was tuned for this type of channel. But, as any protocol, TCP is not tightly coupled with the physical data bearer. Any type of physical layer for data transmission is regarded by the TCP as a data channel with standard parameters as capacity or loss rate.

TCP data transmission is based on packet sending between the nodes. At each node, a congestion control mechanism is implemented to control the partitioning of the resource – the bandwidth. This congestion control mechanism is based on the concept of *congestion window*, which is the amount of data that has been sent but for which no acknowledgment has been received. Because the TCP is a protocol based on all-or-nothing concept, all packets must be acknowledged when received. This acknowledgment mechanism combined with the concept of congestion window is the basics for TCP data transmission control.

In TCP congestion control, there are four distinctive states of the transmission. In each of this state the data transmission rate and the width of the congestion window have distinctive values. These states describe the actual status of the data transmission, so the state in which a TCP connection is presents valuable information about the communication itself.

Shifting from one state to another is done when certain parameters have reached certain limits. For example, when the congestion window size (*cwnd*) is bigger than the *slow start threshold* (*ssthresh*), the TCP connection goes from the Slow Start state to Congestion Avoidance state. Also, when the number of duplicate acknowledges is higher than 3 (usually this means that 3 packets were not received), the connection changes to a Fast Recovery state, a point at which the transmission rate is lowered and the packets are retransmitted. In Exponential Bakeoff state, the transmission rate is lowered, to adapt to the available bandwidth. The TCP diagram for congestion control [8] is presented in Fig. 1.

The parameters and thresholds which generate a state shifting in the TCP congestion state machine are tuned for a wired network. In wireless networks, packet loss can in fact increase the performance of the communication by triggering a packet retransmission.

Also, using a slightly larger congestion window size and a bigger timeout value can increase the efficiency of bandwidth usage. Adapting TCP to wireless data bearers can be achieved through implementation of control algorithms as described in [5] and [1].

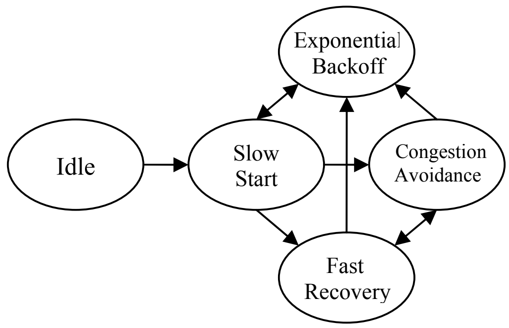

Fig. 1. TCP State diagram for congestion control

From the point of view of the automatic system, the presence of advanced algorithms for performance control in communications can provide supplementary data about the communication channel. For instance, in power control algorithms for wireless channels, the Signal to Interference Ratio is the main parameter which must be controlled. If this parameter is available to the automatic system that employs the wireless communication channel, then a new block for eliminating or minimizing the influence of the model of the communication channel can be implemented.

2.2 TCP Performance Measurement

Measuring TCP performance is important because it offers information about the actual model of the transmission channel. A data transmission channel can be modeled as a pure time delay system with changing parameter. Knowing the channel's parameter in every moment renders possible implementing a compensating system for this time delay.

It is important that the performance measurement over the data transmission channel does not modify normal rates of data transmission and does not introduce instability in the system. Usage of low-bandwidth methods is imperative. One of the methods would be to add custom data to each TCP packet, which would make the estimation of parameters of the communication channel possible. Using an extended protocol as ImTCP is more efficient in terms of time and cost than using custom hardware (routers) for this task [6]. ImTCP stands for "TCP with Inline Measurement" and uses additional data buffers in each TCP packet that allows the implemented algorithm to estimate the available bandwidth.

Other methods of TCP performance measurement, without usage of special hardware, involve sending over the connection a special packet used at application layer to estimate the transmission bandwidth. Somehow similar to pinging, this method has the disadvantage of introducing supplementary traffic through the connection.

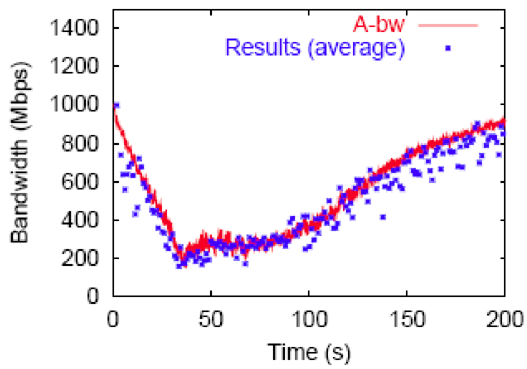

Fig. 2. Measurement results for ICIM method proposed in [7]

Sending "bursts" of data and measuring the interval between packets received or packet acknowledgments can indicate the average time for packet transmission [7]. This Burst-based method, proposed by Cao Le Thanh [7] introduces a new end-to-end bandwidth measurement approach, called ICIM (Interrupt Coalescence-aware Inline Measurement). This approach eliminates the need of usage of custom measurement hardware and the intensive CPU usage at connection ends. The measurements results, as showed in [7], are very satisfactory. Their experimental results are illustrated in Fig. 2.

Using these types of measurement methods does not require big costs for custom hardware and offers a good estimation of the parameters of the data transmission channel used. This information is available at the end of the communication line, and information from intermediate nodes in the network is not necessary, thus increasing the scalability of the solution. These methods can be successfully used to measure a TCP connection over wireless data bearer. Also, custom-made tools for data traffic measurement can be used, as long as they permit on-line measurements of the channel, e.g. Tstat [3], [12]

3. Automated control with TCP communication

As stated before, many of the new automated system architectures rely on long-range communication systems. Wireless communication is cheaper and more standardized, so using it, especially in distributed systems, is almost imperative in terms of efficiency. It is true that the communication layer introduces a time delay almost anytime.

Especially wireless communication can sometimes have big delays which might drastically modify the overall system performance. To eliminate this inconvenience a special structure of control system is required. Also, at supervision level, special structures for time delay compensation could increase the overall performance.

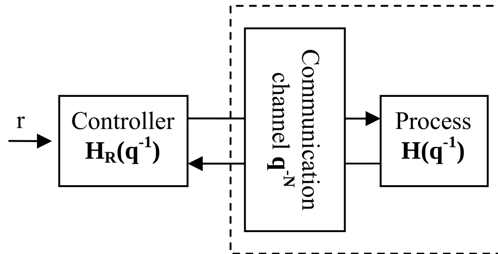

Fig. 3. Standard control structure with time delayed communication channel

3.1 Predictive command

A standard control system can be structured in two important parts: the process that has to be controlled and the controller (the regulator). Usually, these parts are physically separated, so a communication channel must be established between the regulator and the process. Measurements from the process and commands from the regulator are transmitted through this channel, so the channel has to be bidirectional. The channel introduces a time delay both ways.

To compensate for the time delay, the regulator can include a special structure of predictor. The total time delay in the system is q^{-N-M} where N and M are the delays of the transmission channel when the last command was transmitted and when the latest measurement was received. If the channel does not change its parameters too rapidly, we can approximate the total delay as being q^{-2N}, so the effect of one command issued by the regulator will be sensed by the regulator in the process' outputs after $2N$ time intervals.

To successfully control the process, the regulator has to compensate for the time delay. This compensation, called "prediction", is achieved by identifying the process based on the data available to the regulator, calculating the present output and issuing the command that corrects this predicted output. After $2N$ intervals the measured output is available to the regulator and the prediction error can further be used in a new process identification. On-line system identification is described in [9].

To improve the prediction of the system, information from the communication channel can be used to tune the predictor's parameters. As described in paragraph 2, we can measure the performance of the communication channel with good accuracy. Also, information from the physical channel can be used to tune up the regulator's parameters. A structure as the one in Fig. 4 is proposed.

3.2 Supervision through time delayed communication channel

In a control system, the supervision layer adapts the set of references applied to the regulator so as the quality indicators of the process are near the

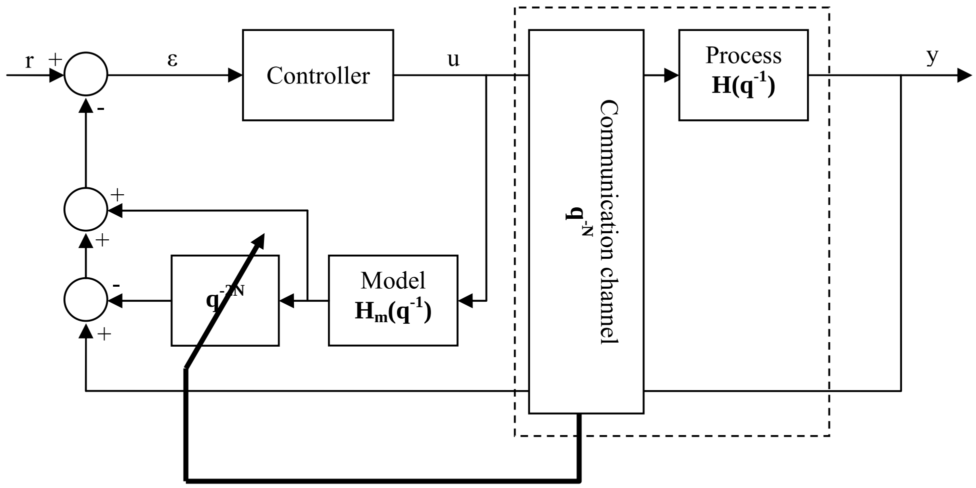

Fig. 4. Predictive control with adjustable parameters according to the delay estimation of the communication channel

required values. The supervision layer needs to acquire from the automated system information about the output of the process and about the quality indicators. At each step, the supervisor makes the following operations: identifies the process based on measured outputs and calculated commands, minimizes the quality criterion and computes the required references for the regulator. The dynamic of the supervision layer is lower than the dynamic of the process, so the operations are executed in a bigger timeframe.

If the communication between the supervision layer and the automated system is made through a time delay channel, and the delay is comparable with the execution time of the supervision algorithm, the optimization can become inefficient. Thus, a time-delay compensation could be required. A MPC method can be used, but identification at each step is not necessary, because the regulator-process system does not change its model too fast in time.

To compensate for the time-delay, the identification algorithm can subtract the pure time delay model of the communication channel, q^{-N}. By eliminating the model of the communication channel from the supervision algorithm, superior performance in terms of quality indicators can be achieved.

In order to subtract the model of the channel, information about the delay must be obtained, by running one of the performance estimation methods enumerated in the second section of this paper.

4. Simulation results

The objectives of the simulation study are to investigate the influence of the communication channel's time delay on the control system. The principle of the architecture is described in Fig. 4. To estimate the delay induced by the

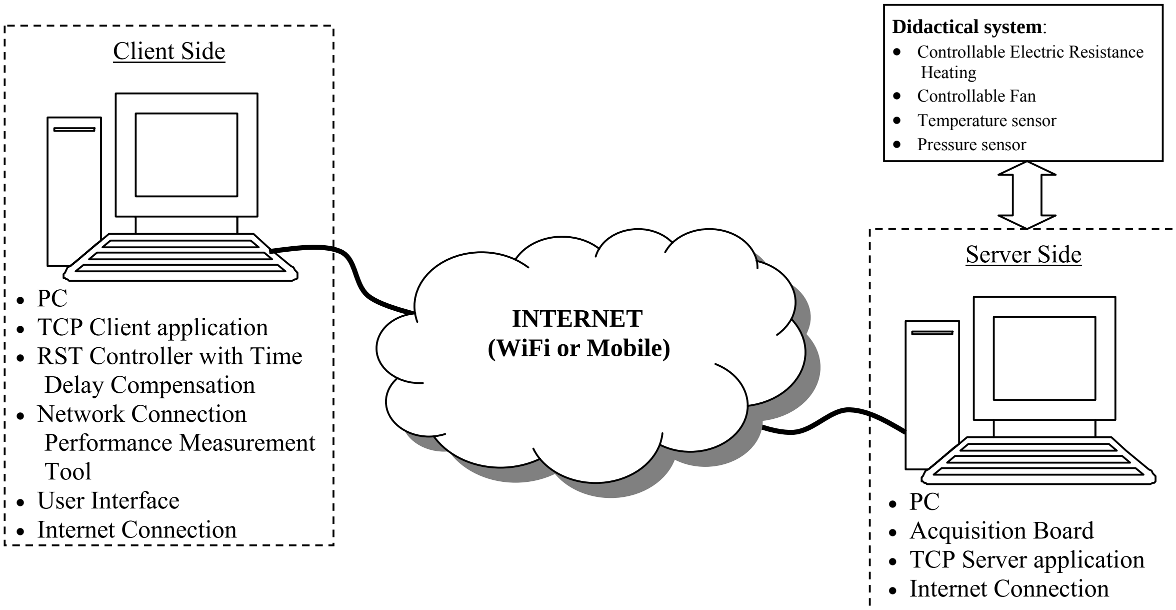

Fig 5. Test application featuring temperature and pressure control in a didactical system, over Internet (with wireless connection)

communication channel, we presume that one of the algorithms in section 2 has been implemented.

4.1 Design of the simulation

The simulation has been conducted in the Matlab Simulink environment. The structure of the system is presented in Fig. 6. The structure simulates the actual system in Fig. 5. Thus, we consider the system composed of a fan, a measurement tube and a pressure sensor inserted in this tube to be described by the continuous transfer function written in the “Real process” block. The real system is also composed of an electric heating resistance and a temperature sensor. But we consider them two distinct systems (pressure and temperature control). The temperature control system can be simulated by a similar Simulink structure. The controller is described by a simpler transfer function.

Please note that the behavior of the system with the controller does not follow the reference! We suppose that this is the behavior we wish the system to have. We also suppose that the process has been already identified and the estimation follows close enough the real model. These two assumptions do not make the results less significant because the process itself is quite simple in terms of transfer function complexity (it is a standard pressure or temperature variation process). Also, the first assumption does not limit the results because it induces a higher degree of generality (we can impose any transfer function for the whole system!).

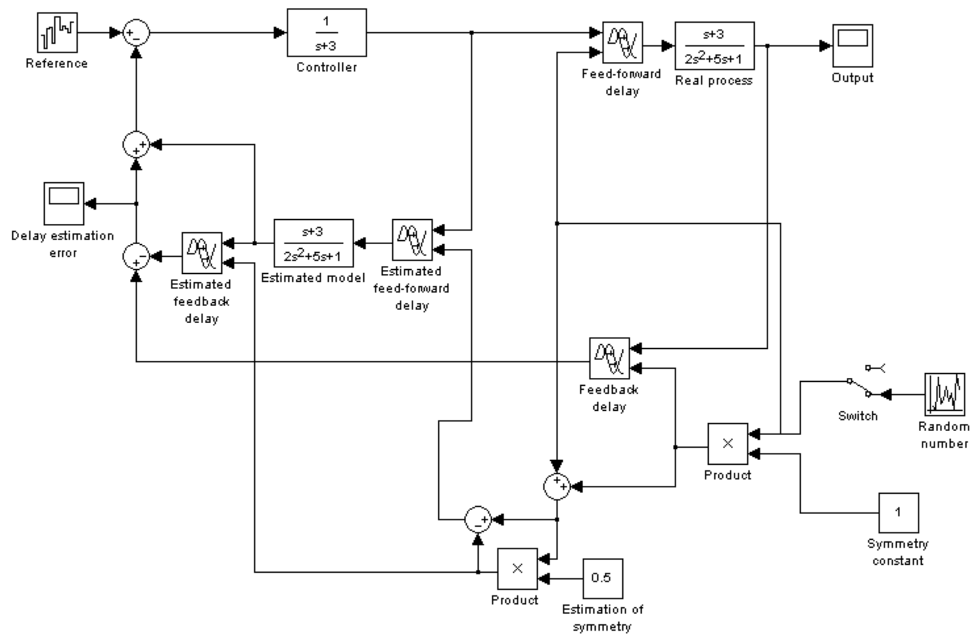

Fig 6. Simulation structure implemented in Matlab/Simulink

To simulate the communication channel, we used several blocks with controllable delays. The duration of the delay is given by the "Random number" block. Turning the switch off, we can simulate the system with no communication delays. Also, a symmetry constant is used; it can change the symmetry of the delay regarding the feed-forward and feedback loops. Thus, we can simulate a channel that has, for instance, the upload link with a lower bandwidth than the download link.

By using the methods to measure the delay in a communication channel, we can estimate only a global delay that sums the upload and the download time delay of the channel. So we need an estimation of the symmetry of the channel, to be able to tune up the predictor. Thus, the block "Estimation of symmetry" sets the actual percentage (in decimals) of the estimated feedback delay. The estimated feed-forward delay will be the difference, so as the sum of the estimated delays is equal to the delay measured from the channel (with one of the methods in section two of this paper).

4.2 Simulation results

The simulation shows the influence of the estimation of the time delay of the communication channel over the overall performance of the system. When implementing a time delay estimation algorithm the error that comes from the communication channel's delay should be minimized. The delay estimation error should thus be as low as possible.

In Fig. 7 we have the result set for the following cases:

A. No communication time delay

B. Symmetrical time delay, with symmetric estimation

C. Two-to-one download/upload time delay ratio with symmetric estimation

D. Two-to-one download/upload time delay ratio with asymmetric estimation, fraction value 0.66

The graphs represent the output and the estimation of the delay. The first column presents the output of the simulation, with the x-axis representing the time (in simulation steps - discrete system), and the y-axis representing the amplitude of the signal. Of course, the output is dependent of the input, and we chose a random input, so that we simulate a system with a rapid-varying state. In this case, to estimate the quality of the control, we measured the difference between the simulation and the “real-case” (simulated real-case). The simulated real-case suffers of perturbations of the channel-delays. The second column thus presents the estimation error. Because it’s known that the controller would eliminate a normal system perturbation, the second-column graphs show the errors introduced by the channel delay. The axes are the same as the ones in the first column.

Based on these graphs, we can draw up the following conclusions:

- The delay has over the system with controller an influence that cannot be eliminated completely
- The predictor minimizes the influence of the time delay, keeping the system in the same working regime (we can notice that the output graphs in situation A and B have the same pattern)
- The precision of the estimation is important and influences the overall performance. The dynamic of the time delay identification algorithm has to be higher that the dynamic of the process

4.3 Usage in real-life application

The results obtained in the simulation indicate that a real-life application that implements data transmission protocols and that provides information about the communication channel itself can benefit of stability improvement if implements the method described in this article.

There are, however, certain aspects that must be taken into account when evaluating the project:

- The dynamic of the system has a value of the same order as the variation in the communication channel. If the dynamic of the process is low, and the communication channel has good performances, the delays can be treated as perturbation and eliminated this way (with the controller in place)
- The measuring method of the communication channel does not introduce further significant delays

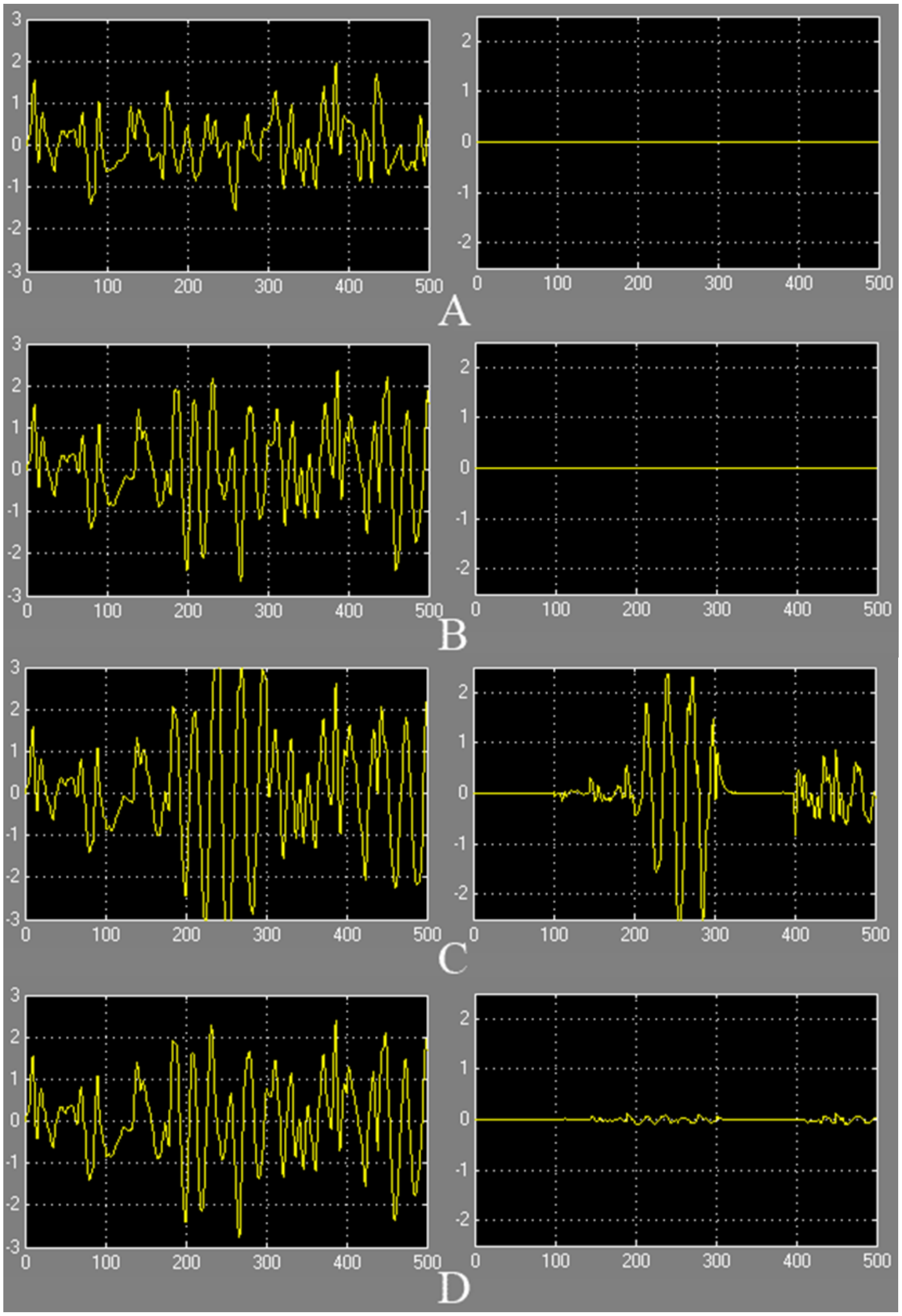

Fig. 7. Simulation results for four distinct situations. The first column contains the output graphs and the second column contains the delay error graphs

- The system permits measuring the properties of the communication channel. In a real-life application, there are practical aspects that can make impossible applying the method: hardware limitations, security aspects, or simply cost.

5. Conclusion

Data transmission is vital in any automated system. Modern technologies improved the control of the communication layer. Measuring the performances of the channel and estimating the time delay introduced in a system is now possible using dedicated algorithms and protocols. Using this information in fine tuning the control algorithm can increase the overall performance and stability.

Acknowledgments

This work was supported by "Idei" and "Parteneriate" Research National Plan PNCDI II, Gr 1044/2007(Idei), 82-095/2008(Parteneriate)

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