TESTBED EVALUATION OF NETWORKED CONTROL SYSTEMS

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Abstract: This work addresses the issue of performance evaluation of advanced control algorithms which are going to be implemented on scalable industrial computer networks. The basic characteristic of these implementations is that information concerning measurements from sensors, commands to actuators and reference inputs is exchanged between the plant and the control system over a real-time communication network. The need to evaluate the performance of such algorithm implementations before commissioning them derives from the fact that the network-induced delay during the exchange of the sensor-to-controller and controller-to-actuator data and the possibility of loss of a data package during transmission may affect the algorithm performance. One way of assessing this performance is by emulating the operation of the algorithm on a test-bed. As test-bed is defined the facility that consists of a computer-based simulation of the plant which is linked to the real communication network and actual control devices on which the algorithm will be implemented. As there are many proprietary and open communication network protocols and standards, unavoidably the test-bed has to be constructed for a specific protocol and standard. In this work a test-bed based on the Profibus standard and its FMS protocol has been realized. The purpose is the evaluation of a control algorithm which will run on one or more controllers that will be inserted in an already operating networked control system. In order to demonstrate the way of using a test-bed for evaluating the performance of a control algorithm the study of the LQC control of a cement milling circuit is presented.

1 INTRODUCTION

The control systems that have their control loops closed via a serial and common communication channel are usually called Networked Control Systems. They present certain advantages over the traditional point-to-point architectures, such as small volume of wiring, distribution of the processing functions to many units, modularity, low cost and quick and easy maintenance. However, they introduce and some new problems arising from the time varying delay that might appear during the transmission of sensor and actuator related measurement data and the possibility of loosing data during one or more sampling periods. The control algorithms are usually designed with the assumption that measurements of the controlled variables can be taken at sampling rates that are either steady or varying within certain limits. Because of the network-induced delays these limits might not be always secured, something that may influence the performance of the control algorithm. The same problem of system stabilization may appear because some packets of measured or command data not only suffer transmission delay but even worse, they can be lost during transmission and they will not arrive by the time of control calculation.

Hence, the need arises to check the performance of control algorithms that have been designed with conventional control theories, such as synchronized control and non-delayed sensing and actuation when they are implemented on networked control systems. This performance is greatly influenced by the type of the network and its traffic. So, there are networks with communication protocols that minimize the likelihood of having long packet delay or packet loss and other that have predictable delay limits. As networks of the second type seem to dominate the industrial sector it would be wiser to invent ways of assessing the performance of control algorithms that

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will be implemented on such networked control systems as reliably as possible. Believing that next to the implementation of the algorithm in the real field conditions is the hardware-in-the-loop simulation of the algorithm, we propose in this work a facility for assessing the performance of the control algorithms which involves the actual controllers and the network that will be used in the industrial field and a computer simulation of the controlled process. This facility is enhanced with generators of network traffic, so that the controller induced traffic added to generated traffic would allow to study the behaviour of the controller under varying traffic loads. The traffic load imposed by the generator simulates the load inflicted on the network by other control applications that the same network is used for.

The proposed test facility consists of at least three units. The first unit is a PC-based computer station which hosts a process simulation package such as MATLAB (Math Works, 1996), interfaces and links to an industrial network, such as FMS Profibus (DIN, 1992, Tovar, 1999a). It also has the necessary software that allows the transfer of data between the controllers and the process simulation package. The second unit is a PC-based station of the network which simulates the traffic load of the control applications. The third unit is another PC-based network station that implements the algorithm that controls the simulated plant. This facility is scalable and can be expanded to accommodate additional network stations that will implement the control of other variables of the simulated plant. Although the FMS protocol has functions and services that are more than those required for the pure automatic control of process variables, this protocol has been selected as the protocol of the first attempt to build a test-bed because it can include traffic that is related with the functions of the supervisory and process operations control. These functions are an integral part of the operation of any industrial complex and in small plants using different Profibus protocols for the pure automatic control and the higher level functions increases the development and running cost. Therefore, this test bed may be used to evaluate a mixture of higher and low level control operations and its use is mainly addressed to the case of the small process plant.

In this work a realization of the above test-bed concept has been made and is presented. In this realization the proposed test facility has been expanded to include a fourth station that monitors the network operation and realizes the supervisory and monitoring functions of the plant simulation. How these facilities can be used to assess the performance of an algorithm on a networked control system is demonstrated by realizing the LQC networked control of two loops of a cement milling circuit with the FMS Profibus protocol. Various network parameters are adjusted and the use of the developed test-bed to evaluate the performance of the considered LQC control algorithm was studied under a specific network traffic. This demonstration shows the possible use of the test-bed to checking whether a control algorithm can be implemented in an existing networked control system without driving the system to instability. Also, it shows how one can tune the network to accommodate the insertion of the new algorithm.

2 THE PROFIBUS INDUSTRIAL NETWORK

Vendor-independent standardized networks for control, supporting the open system concept, have emerged over the last years. Profibus is one of the available standards that have been approved by CENELEC (EN, 1996). Numerous Profibus installations have been reported. The Profibus MAC protocol is a simplified version of the timed-token-bus protocol (IEEE, 1985, Tovar and Vasques, 1999b). According to this protocol master stations of the network get the bus access when a data object called token is passed to them. During operation of the network the station with the token transmits data frames until it runs out of data frames or the time it has held the token reaches a limit. Actually there are two types of frames that are transmitted. The synchronous and the asynchronous ones. The synchronous ones correspond to critical data that must be transmitted within the holding time of the token. The Profibus protocol allows one synchronous package per token holding time to be transmitted and if time is left the asynchronous transmission is initiated and is terminated even if that requires the violation of the holding time limit of the token.

The time delay of a message is defined as the difference between the time when the source node begins the process of sending a message and the time when the destination node completes reception of this message. This time delay must be less than the target rotation time, a network timing parameter that can be set by the user and expresses the time elapsed between two consecutive receptions of the token by the network station. A dominant part of the message time delay is the slot time which defines the maximum timing period that the sender of a package must wait for the receiver response. If the sender does not receive the response from the receiver within this timing period the sender repeats the transmission of the same package. By adjusting the token rotation time (trt) and the slot time (tst) and keeping all the other timing parameters of the network at preset values is a first level tuning of the network in order to cope with the satisfaction of deadlines of tasks that have to be executed by the network stations.

3 THE FMS TEST-BED

The diagram in Figure 1 shows pictorially the architecture of the developed test-bed which consists of four different stations. Each station plays a specific role in the network and is loaded with software that is appropriate for its role. The first station is used for simulating the process to be controlled as well as the sensors and the actuators of the controlled plant. The second station simulates the control functions that have already being using the network. In fact, it generates network traffic similar to the one that is expected to be produced by the aggregated operation of all the other control functions except the ones that we are going to introduce. This traffic is exchanged with the first station and is produced by a generator which can be preset to send a number of packages the data size of each package being determined statistically according to the Poisson distribution.

When a master holds the token it may establish a master-slave communication procedure with process relevant devices, such as sensors and actuators for exchanging data. Typically, the process relevant devices are accessed through a slave network interface whereas the distributed control algorithms reside at master stations. The sampling and activation of the sensors and actuators that are related with the operation of the new control strategy is carried out by the master station on which the new control algorithm is running. Finally, the fourth station is a monitoring station of the network operation. By means of this station the various timing parameters of the network can be measured and the exchange of frames among the network stations can be observed and recorded. Each station is linked with the common data transmission medium by the use of the Profibus interface card PB-FM-1MS made by Softing (Softing, 2003) and the necessary software on the host PC which implements the levels 2 and 7 of the FMS protocol of the Profibus standard. Data exchange between the PC and the card takes place through a dual port memory. The card configuration is carried out by the Profibus window NT software which installs the card driver and allows the user to set up the driver parameters. The parameters are those that are related with the network baud rate, the various network parameters, such as token rotation time, slot time, etc. In the first station where the plant dynamics are simulated, the control systems simulation environment of MATLAB is installed. It communicates with custom-made application

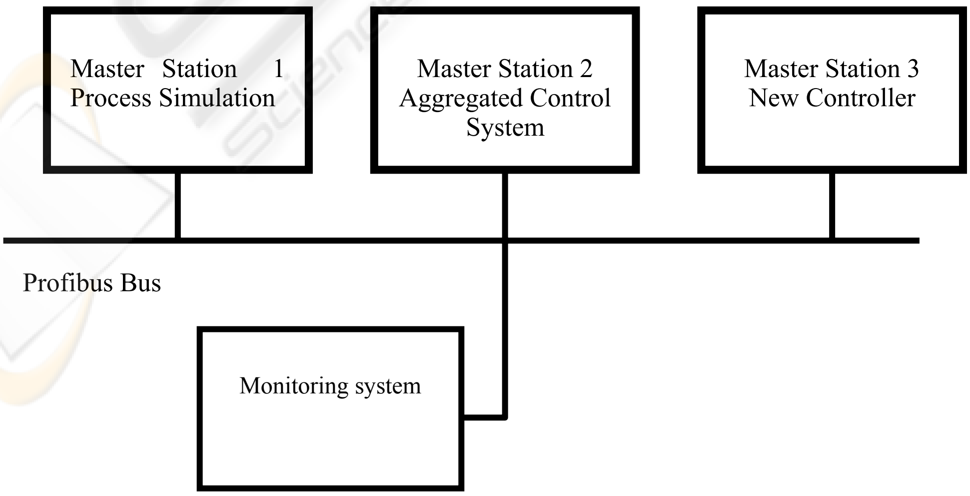

Figure 1: The architecture of the test-bed

software in C which creates virtual objects of the plant sensors and actuators and sends and receives the output and input data to the plant model by incorporating services of the application layer of the FMS protocol. In Figure 2 the architecture of the installed software is pictorially depicted.

4 NETWORKED CONTROL OF A CEMENT PLANT

Next, how the developed test-bed has been used to evaluate the performance of the networked control of two critical parameters of a cement plant will be demonstrated. The considered control functions are implemented on an existing Profibus network which is supposed to be used for the control of other variables of the same or other processes of a plant. The insertion of these two new functions inflicts additional traffic to the existing network and for this reason both the influence of this traffic on the stability and performance of the already running functions has to be evaluated and the performance of the new algorithms need also to be checked for compliance with the control specifications. In fact, one can assume that there are already known limits for the existing control functions on their execution deadlines. This will allow us to impose range limits on the network tuning parameters the values of which will be determined in a way that satisfies the deadlines of the new network control functions.

In this work this assumption is made and the performance of the considered plant is evaluated for various network loads that the operation of the existing control functions might inflict on the network. First, a brief description of the control problem of the cement plant is presented. The basic process unit in the production of cement is the cement milling circuit. Such units are fed with raw material which after being ground is introduced into a high efficiency classifier and separated into two classes.

The tailings (refused part) are fed back into the milling circuit while the finished product (accepted part) exits the milling circuit. In the schematic diagram of Figure 3 the milling circuit principle is shown (Magni, 1999). The classification of the material is driven by the rotational speed and by the air flow rate of the classifier. The load in the milling circuit depends on the input feed (fresh feed plus tailings flow rate) and on the product flow rate that depends in a non-linear way on the load in the milling circuit and the hardness of the material. There is a different upper limit of the load for each hardness value which leads to circuit instability, while keeping the load at a low level will result in the fast wear of the mill internal equipment.

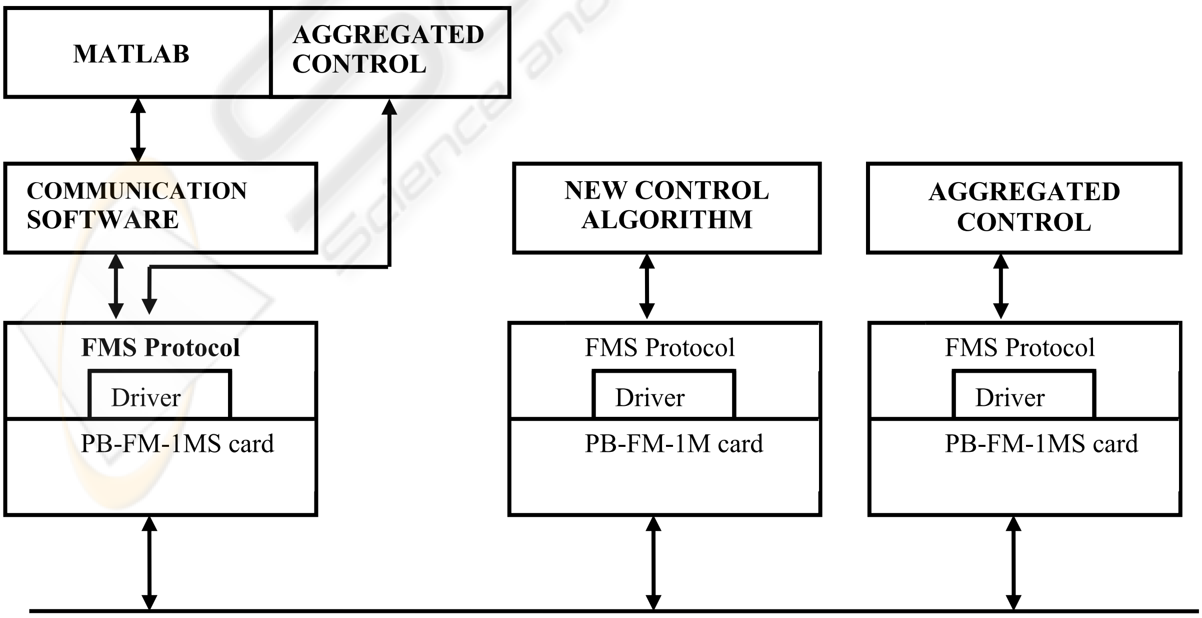

Figure 2: Software architecture of the Profibus stations

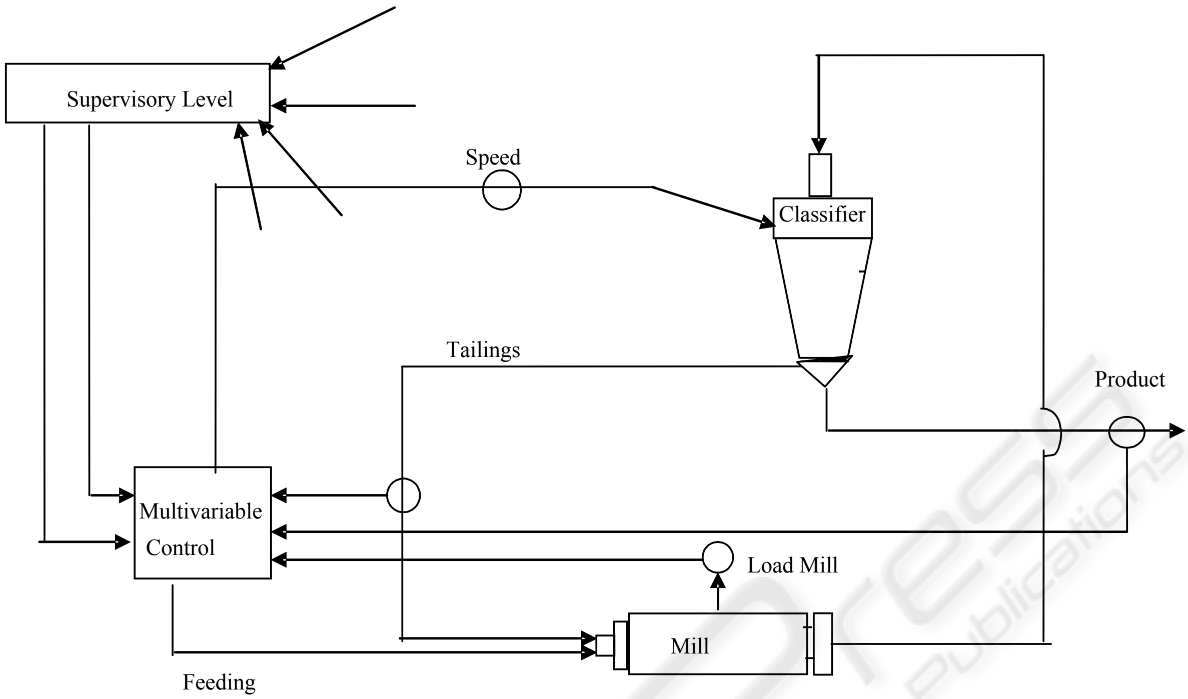

Figure 3: the milling circuit

A multivariable control technique, based on Linear Quadratic Control (LQC) theory, has been introduced (Van Breusegen, 1996) to deal with the instability problem. With this technique two outputs, namely the product flow rate (y_r) and the load (z) are simultaneously controlled by using the two available inputs, that is the feed flow rate (u) and the classifier speed (v). For the implementation of the LQC algorithm on the networked control system the second master station was programmed to perform this algorithm. In the first master station the plant dynamics without the LQC control were simulated in the MATLAB environment. During this simulation the solution of the differential equations is carried out at every sampling instant and then the data of the controlled variables y_r and z are read by the second master, when this second master holds the token. Also, within the same token holding time the LQC computations are executed by using the received data and the computed corrections for the manipulated variables u and v are sent to the first station where they are sampled in a similar way. Then the token is passed to the third station which generates data packages of sizes that are randomly selected according to the Poisson distribution. These packages are also read, enhanced by the data of the cement plant and retransmitted over the network. There are certain known deadlines for sending and receiving data from the plant simulation, equal to the sampling rate of each algorithm. To meet these deadlines for a known network baud rate, the timing parameter of the maximum token rotation time (trt) and the slot time (tsl) have been preset. Also the maximum retry limit (max_retry_limit) is set to three. If, however these figures are not correct or there are bursts of heavy traffic in the network, sensor measurements and controlled variables updates might not occur within the deadlines. This might drive the controlled variables to deviations from the desired transient and steady state specifications. By obtaining a recording of the variations of the considered variables of y_r and z over a horizon of sampling instants at various traffic loads, possible instabilities and deviations from the desired transient and steady state specifications may be traced down. Then, new tuning parameters may be tried.

5 TEST-BED EVALUATION

A number of experiments were conducted to show the effect of different values of network timing parameters on the performance of the networked control of the cement plant under varying network loads. The study was conducted under three different loads, namely for 5, 50 and 100 packages. The size of each package varied from 0-510 bytes, randomly defined by the Poisson distribution. The experiments were conducted for two sets of trt and tsl values, that is for tsl=3.5msec and trt=10msec and tsl=3.5msec and trt=2msec. In order to compare the obtained test-bed results with the ideally expected responses, the curves in Figure 4 are given. They have been obtained from the MATLAB simulation of the networked control of the cement plant. The test-bed results for a network load of 50 frames, trt=10msec and tsl=3.5msec are presented in Figure 5. The results for the same network load and tsl value but for trt=2msec are presented in Figure 6.

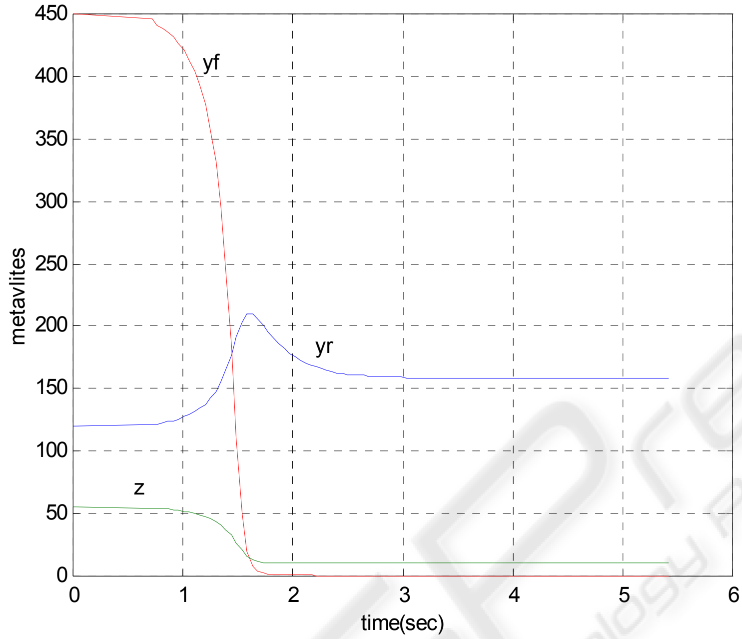

Figure 4: MATLAB Simulation of the LQC control of the cement plant

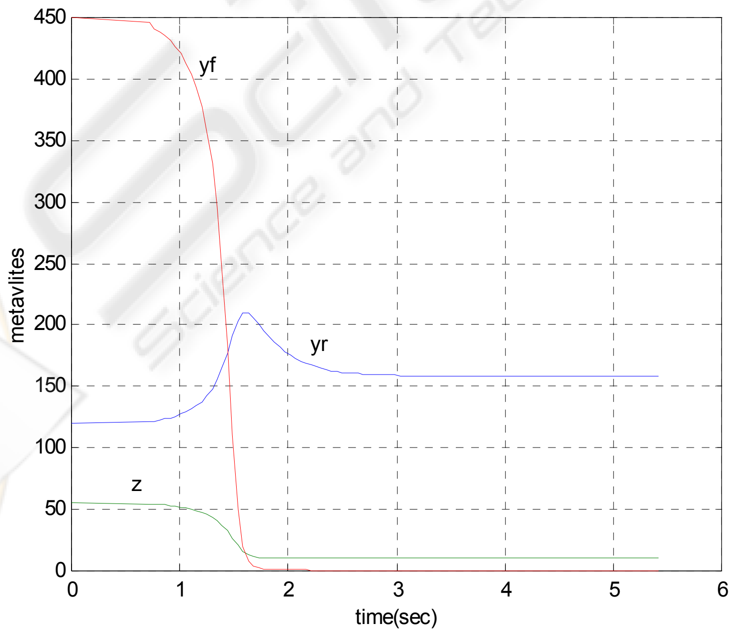

Figure 5: Plant response from the test-bed implementation of the LQC control of the cement plant for g=50, tsl=3.5msec and trt=10msec

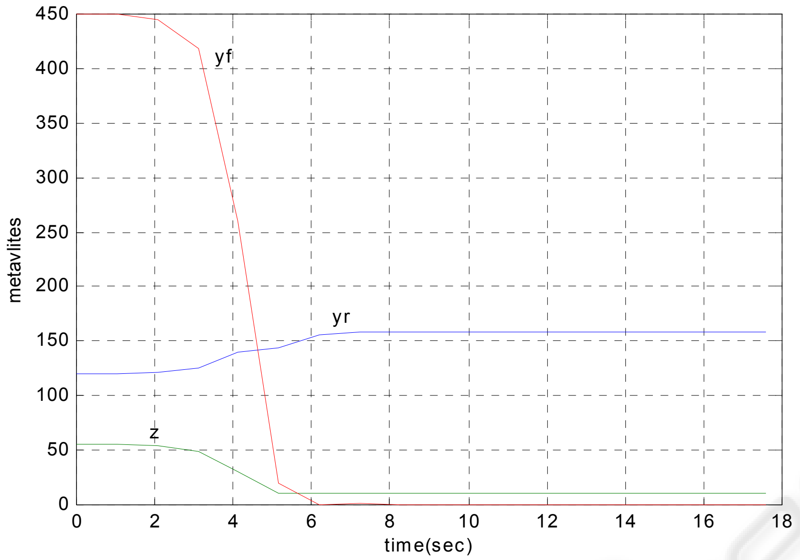

Figure 6: Plant response from the test-bed implementation of the LQC control of the cement plant for g=50, tsl=3.5msec and trt=2msec

From the curves of Figures 4, 5 and 6 one can conclude that the network delay has a small negative influence on the settling time of the plant variables when the trt =10msec. The settling time of the product flow rate (y_r) and the mill load (z) is around 3 and 1.8 time units respectively. These times are very close to those predicted by the MATLAB simulation. On the contrary, at trt=2msec the difference from the simulation is significant, being around 8 time units for the product flow and 5 time units for the load. This is quite an expected behavior as at small token rotation times the possibility of not completing the sampling of the sensors and the computation of the algorithm is quite high. Therefore, according to the Profibus operation the computations will be concluded by violating the trt time. Consecutive violations added up over the time will result to omit one or more computations at certain sampling times, a condition that is known to lead to a deterioration on the loop performance and instability. However, problems of instability are not monitored for the considered network load. Although, one verifies practically what is most likely to expect, the use of the test-bed can provide to him additional quantitative information for the responses of the networked control system Then, on the basis of this information one can take decisions for the trt and tsl values which can satisfy the performance of the new control system without affecting the performance of the already existing control functions.

6 CONCLUSIONS

A test-bed with four master stations for evaluating the performance of designed networked control algorithms of physical processes has been developed and its correct operation has been tested. The network protocol implemented by the test-bed is the FMS Profibus protocol. The conducted tests involved the quantitative comparison of the responses of the product flow rate and load of a milling circuit of a cement plant to different network data loads. They can be attributed to the use of the network for other control operations in addition to those of the cement plant. The comparison has disclosed that as it was expected, the network delay at small token rotation times influences the response and especially the settling time. The use of the test-bed can provide the necessary quantitative information which will allow somebody to trade off the network loading with more control functions at the expense of performance degradation.

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