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Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 119 (2015) 828 – 833
Procedia Engineering
www.elsevier.com/locate/procedia

13th Computer Control for Water Industry Conference, CCWI 2015

A CONTROL SIMULATION TOOL FOR ONLINE DEMAND CALIBRATION

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Abstract

Developing fast calibration algorithms is an important step towards the online simulation of hydraulic water networks. The objective of this paper is to report a new demand calibration approach by using algorithms from control theory. We propose a multivariable PID control where the control parameters are identified by a system identification approach and the system matrix is decoupled. In this control approach the measured flow variables are regarded as dynamic set-points. The controllers use the demand values as manipulated variables in order to control the flow variables to the measured flow. The concept was applied successfully using a small test-network.

Peer-review under responsibility of the Scientific Committee of CCWI 2015

Keywords: Water distribution networks, Network security, Real-time demand calibration, PID controllers, Least-squares method

1. Introduction

In recent years the online simulation of hydraulic water networks has been gaining ground among professionals dedicated to the analysis of water distribution systems ([1], [2]). One of the challenges of the online simulation approach is to know in real time all relevant boundary conditions of the network. The parameters governing hydraulic and transport network models are in most cases a rough estimation. This is due to the fact that they either can't be measured directly (i.e. diameters, roughness) or underlie strong variations like water demands. Measurements of network state variables like pressure, flow rate, tank level, concentration, conductivity can however be used to calibrate these parameters [3]. Carpentier gives a definition of the observability problem as the one of determining whether the available set of measurements provides sufficient information for the state estimation [4]. Two levels of observability are defined. The topological observability, assessed by graph theory and the algebraic observability which is determined by analyzing the sensitivity matrix. The choice of the measurements and the measurement points

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1877-7058
Peer-review under responsibility of the Scientific Committee of CCWI 2015
doi:10.1016/j.proeng.2015.08.946

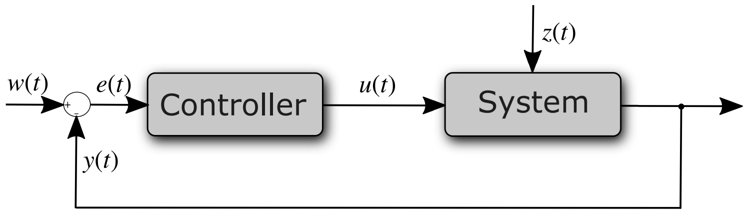

Fig. 1. Basic control loop

must ensure the observability of the network but also prevent small errors in measurement resulting in incorrect estimations of the parameters [5].

Using optimization approaches fitness functions may be selected for the parameter calibration. A review of several fitness functions and entropy-based criteria is given by de Schaetzen [6] or Savic [7]. A standard approach for overdetermined systems is the least squares formulation that minimizes the deviation between the observations and the model. In [8] a modified least-squares criterion is used that is more robust against outliers. The problem is solved by using Genetic Algorithm (GA). By simplifying the network a pseudo-real time solution can be found (about 15 min.). In [9] the gradient type Levenberg-Marquardt (LM) method has been applied to a weighted least squares (WLS) method for water distribution networks. Gradient type methods are more efficient, but as the WLS criterion may exhibit several local minima and maxima genetic algorithms may be more robust. Kapelan proposed a hybrid GA/LM approach that uses a genetic algorithm for the first iteration steps to come close to the solution [10]. Another approach suggested by Piller is to convexify the WLS criterion with addition of a Tikhonov regularization term that penalizes departure from a prior solution [3].

To improve the performance of the hydraulic and transport calibration this paper suggests a calibration algorithm inspired by control theory. The proposed algorithm keeps up the calibration of the strongly varying parameters to improve the over all accuracy.

In Section 2 the application of the control algorithm to the water distribution network is described. First the basic concept of system control is explained followed by details on the application of the concept. Section 3 defines a test scenario and presents the results of the control algorithm for different sets of control parameters. The results are discussed in Section 4 and finally a conclusion is given and potential for improvement in future research is pointed out.

2. Calibration Algorithm

2.1. Control Theory

Control theory deals with the behavior of dynamic systems and how to modify this behavior. The objective is to control a system in a way that its outputs y(t) follow a desired value or set-point w(t). To do so the difference between the output signal and the desired output, also called the error signal e(t), is used as feedback u(t) to the system through some sort of actuator (Figure 1). The major points of interest in control theory are stability, observability and controllability .

The conversion of the feedback signal into a actuator signal is done by a controller. In industrial applications there are a numerous approaches. The most common one is called the PID-controller and the controller output is given by:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

with the tuning parameters:

K_p : Proportional gain factor,
K_i : Integral gain factor,
K_d : Derivative gain factor.

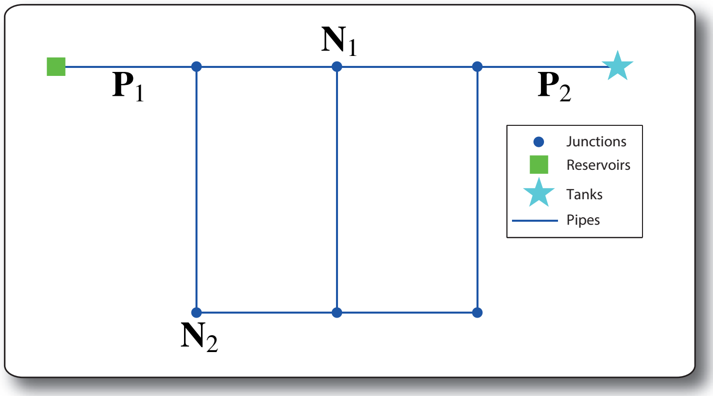

Fig. 2. Exemple network with demand nodes N_1 and N_2 and measurement points P_1 and P_2.

The proportional term produces a feedback component that is proportional to the magnitude of the error by multiplying it with the proportional gain. The integral term contributes a component proportional both to the magnitude and the duration of the error. This accumulated error is multiplied by the integral gain. The magnitude of the derivative contribution is determined by the rate of change in the error signal multiplied by the derivative gain. The determination of these tuning parameters can lead to big differences in speed, accuracy and stability of the system.

2.2. Application to Calibration

The control based calibration algorithm is based on the idea that the system is represented by the hydraulic simulation model of a water distribution network and the measurements of flow in the actual network are the set points for the system output. In this scenario the difference between the measured flow and the calculated flow gives the error signal for the feedback. The actuator the controller output acts upon is given by the demand factors at the consumption nodes. In an ideal scenario this setup enables us to control the flows to follow the measurement and by that to find the actual demand factors which are given by the controller output.

For testing this approach a simple water distribution network has been constructed using Epanet. The network contains a reservoir for supplying water to the network, a tank and six junctions that are connected in a looped manner as shown in Figure 2. Inside the network the nodes marked as N_1 and N_2 are chosen to be consumption nodes, where the actual demands are applied. Further there are two pipes indicated by P_1 and P_2 which are chosen as measurement points for the flow rate. Due to the fact that a change in the volume flow at either of the consumption nodes influences the flow rate at both measurement points, the application of a multiple input multiple output (MIMO) control algorithm is appropriate.

Preparing the control-algorithm for application to the network requires three major steps. First the identification of the system matrix, second the decoupling of the system matrix and third the estimation of the gain parameters. The objective of the identification step is to analyze the dependencies between the actuator signal at the demand nodes and the effect on the flow at the measurement pipes. To do so a finite difference approximation is used to determine the system matrix G.

$$G = \begin{pmatrix} 4.95 & 4.26 \\ -4.95 & -5.63 \end{pmatrix}$$

The system matrix gives the relation between the changes in consumption at the demand nodes and the change in flow at the measurement points. It is obvious that there are strong interdependencies. To break up these interdependencies in the second step the system matrix is transformed for the main components using the eigenvector matrix V.

$$D = V^{-1}GV \tag{2}$$

For the test network this results in the diagonal decoupled system matrix D.

$$D = \begin{pmatrix} 2.28 & 0 \\ 0 & -2.96 \end{pmatrix}$$

Once the system matrix is decoupled it is possible to apply two independent PID controllers to the water distribution network. The next step is the parameter estimation for the gain factors. For the proportional gain factors a good estimate is given by the inverse value of the eigenvalues from the system matrix. Using the equation for calculating the time constant

$$T_n = K_p/K_i, \tag{3}$$

the integral gain parameters can be determined by choosing T_n. The derivative controller component will not be used for the algorithm presented in this paper.

3. Results

For testing the robustness of the calibration algorithm described in the previous chapter a theoretical scenario has been devised on the test network shown in Figure 2. The objective of the scenario is to evaluate the ability of the calibration algorithm to follow changes in the nodal demand for an initially calibrated system. In this scenario the water demand at the nodes N_1 and N_2 is assumed to follow a continuous demand pattern modeled by a cosine and a sin pattern with a peak amplitude of $1[m^3/s]$ and a mean of $0[m^3/s]$. The real demand and flow values are sampled with a constant rate. Within each measurement sample a fixed number of control steps is taken.

Figures 3 and 4 show the results for the chosen scenario with different choices of gain parameters. Shown in the left column are the flow measurements at pipes P_1 and P_2. The right column depicts the demands at nodes N_1 and N_2. For the diagrams in general the continuous line gives the sampled value at the measurement points. The dashed line shows the resulting value from the calibration algorithm.

In Figure 3 the gain factors are chosen as $K_{p,1} = 0.44$, $K_{i,1} = 0.04$ and $K_{d,1} = 0$ for the first controller and $K_{p,2} = -0.34$, $K_{i,2} = -0.03$ and $K_{d,2} = 0$ for the second controller. The controller uses small steps for reacting to the changes in demand and especially the second controller has problems reaching the desired demand. For Figure 4 the gain factors are chosen as $K_{p,1} = 0.44$, $K_{i,1} = 0.09$ and $K_{d,1} = 0$ for the first controller and $K_{p,2} = -0.34$, $K_{i,2} = -0.07$ and $K_{d,2} = 0$ for the second controller. In contrast to the previous example both controllers manage to reach the desired demand values within the 4 control steps. For smaller values of the time constant T_n the system becomes unstable and starts to oscillate with an increasing amplitude.

4. Discussion

It can be seen that the setup in Figure 3 reacts slower to changes in the water demand and that the four iterations of the control loop are not enough for reaching the set-point. This can easily be explained by the fact that the characteristic time constant $T_n = 10s$ is bigger than for the configuration used for the scenario in Figure 4 with $T_n = 5s$. This shortcoming can easily be counteracted by adding additional control loops. The effect on the performance of the algorithm should be minimal due to the low computational cost of the performed calculations.

In contrast, the scenario shown in Figure 4 reacts faster to changes in the water demand and manages to follow the sampled flow measurements more closely. But looking at the trajectory of the demand it is obvious that there is a bigger variance in the output signal of the controller. Though not being a problem for the displayed case it might be problematic in cases where there are bigger deviations in the demand signal from the linearization point where the system matrix has been determined. In effect, the system could become unstable and the algorithm unable to find a calibration.

It is obvious that choosing the gain parameters is a compromise between the speed of the algorithm on the one hand and its robustness on the other. The derivative controller component has not been used in the scenarios presented in this paper. Though it is possible to speed up the controller by using the derivative term it further adds to the problem that the system may become unstable. This is due to the fact that it adds to the tension between speed and robustness.

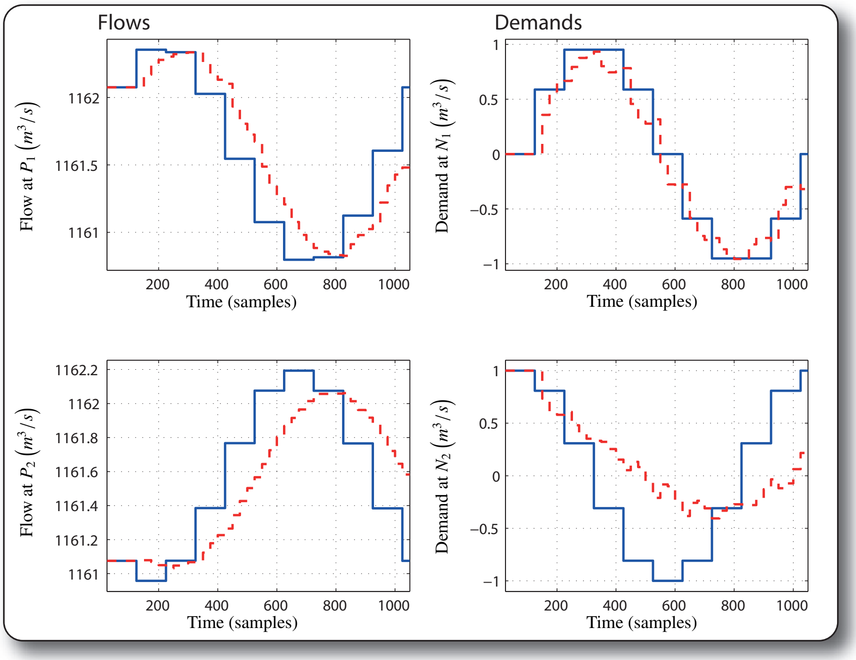

Fig. 3. Result for demand calibration based on PID controllers $K_{p,1} = 0.44$, $K_{i,1} = 0.04$, $K_{p,2} = -0.34$, $K_{i,2} = -0.03$.

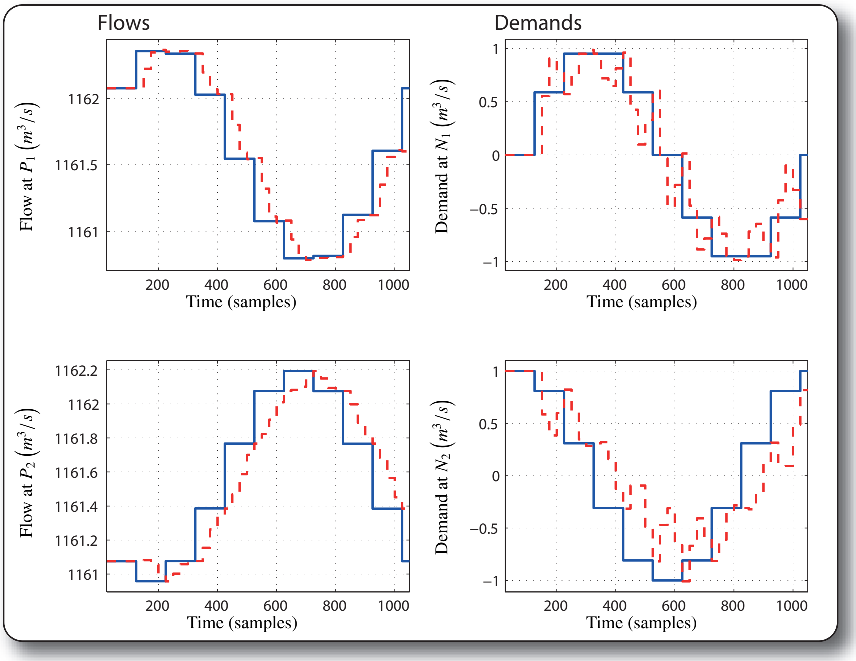

Fig. 4. Result for demand calibration based on PID controllers $K_{p,1} = 0.44$, $K_{i,1} = 0.09$, $K_{p,2} = -0.34$, $K_{i,2} = -0.07$.

The main advantage of the presented algorithm is the speed of the calibration due to the low computational cost of the calculations performed during the control loop. This means it is possible to perform a multitude of calibration steps between the measurements to give accurate results and still have a high sample rate for the measurements.

Right now the algorithm is limited to systems with a square structure, meaning the same number of measurements as points for actuation. There are a number of possibilities to generalize the approach and thus apply it to bigger networks. In bigger networks individual consumers are replaced by consumer groups with a common demand pattern. Using the measurements for calibrating the demand multipliers of these patterns makes it possible to address a bigger number of consumers. Further, the singular value decomposition (SVD) can be applied to systems with a rectangular structure, thus making it possible to use more measurements than demand patterns. A fully automated application of the is not possible yet since the gain parameters are determined by hand based on the system matrix and stability behavior of the system.

5. Conclusion and Future Work

In conclusion it has been shown that it is possible to use a multivariate controller algorithm for adjusting the demands of a calibrated network for changes. The algorithm is easy to implement, but requires the decoupling of the measurement to work properly. Due to the simple nature of the calculations performed inside the control-loop the computational cost can be kept very low. Further, as long as there are no significant changes in flow condition, the algorithm is robust with respect to changes in the flow velocity. Before using the algorithm it is necessary to identify and decouple the system matrix. The estimation of the gain parameters for the controllers is right now done manually.

Further research is necessary for the automatic estimation of the control parameters for a more efficient use of the algorithm. The example presented here shows the application for two distinct consumption nodes. For a practical application in a bigger network a large number of consumptions nodes has to be addressed. To do so in further research clustered consumer groups will be used that describe the demand multipliers for multiple nodes. In the other direction the amount of measurements is limited by the amount of actuators. For a more efficient use of information the use of the singular value decomposition instead of the eigenvalue decomposition is being looked into.

Acknowledgments

The project is supported by the German Federal Ministry of Education and Research (BMBF; project: 13N12180) and by the French Agence Nationale de la Recherche (ANR; project: ANR-11-SECU-006).

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