A Control-Oriented Hybrid Modelling Approach for Sewer Networks: Barcelona Case Study

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Abstract: A simplified sewer nework modelling approach based on the hybrid linear systems framework is discussed. It involves both continuous and discrete variables to include a novel approximation of the overflow and flow over weirs phenomena. The model is validated against data provided by a simulator based on a physical model and is shown to be easily adapted to an optimal/predictive control setting that allows the computation of optimal control actions through the solution of a mixed-integer programming problem.

INTRODUCTION

Combined sewer networks are present in many large cities all over the world. These networks carry both wastewater and stormwater together. During low to moderate rain events, this water is carried to wastewater treatment plants, where it is treated before being released to the receiving environment (usually a river or the sea). However, during heavy-rain events the network capacity can be easily overloaded, causing urban surface flooding as well as untreated water discharges to the environment, known as *combined sewer overflows* (CSO), to happen.

To avoid these unwanted discharges, detention tanks are usually built along the network to store the water during the peak rain intensity periods and later release it at lower flow rates. Since these infrastructures are clearly expensive and difficult to locate in urban areas, its efficient operation has become a topic of major interest.

The efficient managment of combined sewer networks is strongly dependent on rainfall predictions, which are only available with acceptable precision for short time periods. Thus, real-time control is regarded as the best option to provide control actions every few minutes computed from the most recent rainfall predictions as well as data obtained through network monitoring [1]. The physical model for flow routing in sewers (open-channel flow) involves the solution of a set of partial differential equations (the Saint-Venant equations), which is not suitable for the computation of control actions in real time due to the high number of variables that would be involved in the discretization and the nonlinear nature of the equations. Therfore, simplified mathematical models for model-based control have been developed in the recent years by [2, 3, 4, 5] among others. The model developed in this work provides a better approximation of flow over weirs and, specially, the overflows in the network nodes than in previous works. A new overflow model has been developed to keep track of the overflow volume to later return it to the network improving considerably the flow prediction downstream of the overflow point. Other advantages with respect to some provious modelling approaches are the fact that the network topology is obtained directly from the real nework and that parameter calibration can be carried easily from tha data provided by any simulator based on the physical model.

MODELLING APPROACH

The model describes flows through pipes, gates and weirs and volumes stored in tanks in a discrete time setting. The main equations account for delay and wave attenuation in pipes and mass balance in junctions.

The overflows causing urban flooding are described by means of piece-wise linear equations defined in pipe junctions as $f(t) = a_f \max\{0, q_{in}(t) - q_f^{max}\}$. At each junction, a maximum outflow q_f^{max} is determined, and when the inflow $q_{in}(t)$ to the junction is greater than the maximum outflow, a fraction $a_f \in (0,1)$ of the extra flow is considered as overflow $f(t)$. The introduction of paramater a_f is a new feature with respect to previous works that has been proven to provide better approximations. Flow over weirs is defined in an analogous way.

Another new feature of the proposed model consists in keeping track of the overflow volume by means of a virtual tank. This volume is stored in the tank until the overflow has finished and then is returned to the network as an inflow to the junction where the overflow has previously occured.

All the logical conditions that appear in overflow, weir, and flooding volume descriptions are reformulated into linear inequalities involving both continuous and discrete variables by means of the *Mixed Logical Dynamic Systems* approach developed by [6]. This resulting set of inequalities is solved together with the system dynamics by means of a *Constraint Satisfaction Problem* (CSP, [7]) for simulation purposes. The CSP is compactly expressed as a *Hybrid Linear Delayed System* of the form

$$\sum_{i=0}^{T} M_i X(t-i) = m(t), \quad \sum_{i=0}^{T} N_i X(t-i) \leq n(t), \tag{1}$$

where $X(t)$, is the vector of system variables (continuous and discrete), $M_i, N_i,\ i = 0 \ldots T$, are matrices of suitable dimensions collecting the system dynamics and MLD inequalities, and $m(t), n(t)$, contain disturbance data. For simulation purposes, flows through gates are regarded as known inputs and rain inflows as disturbances. Rain inflows are computed from sensor data using the *Kinematic Wave Model B* implemented in the simulator [8].

CASE STUDY AND MODEL VALIDATION

The modelling approach has been applied to the Riera Blanca Sewer Network, which is a part of the Barcelona sewer network. After a topological simplification process, the network consists of 147 pipes, 2 tanks, 10 gates and 3 weirs. An implementation of this network in the sewer network simulator MOUSE [8], which simulates a complete physical model based on the Saint-Venant equations, has been provided by CLABSA (Clavegueram de Barcelona S.A.), the company responsible of its management. Using this complex model, several rain scenarios, also provided by CLABSA, have been simulated with fixed positions of the network gates. The data obtained in this way has been used for the model calibration: owtflows of pipes, junctions, weirs and overflowing nodes are computed as functions of the parameters and the inflows provided by the simulator and compared against the outflows provided by the simulator. This comparison is performed for equispaced values of the parameters within their limits and the best combination is chosen. Since the parameter calibration is performed independently for each network element, only two or three parameters are involved in each computation. Finally, the parametres obtained for all the calibration events are averaged to obtain the final parameter set.

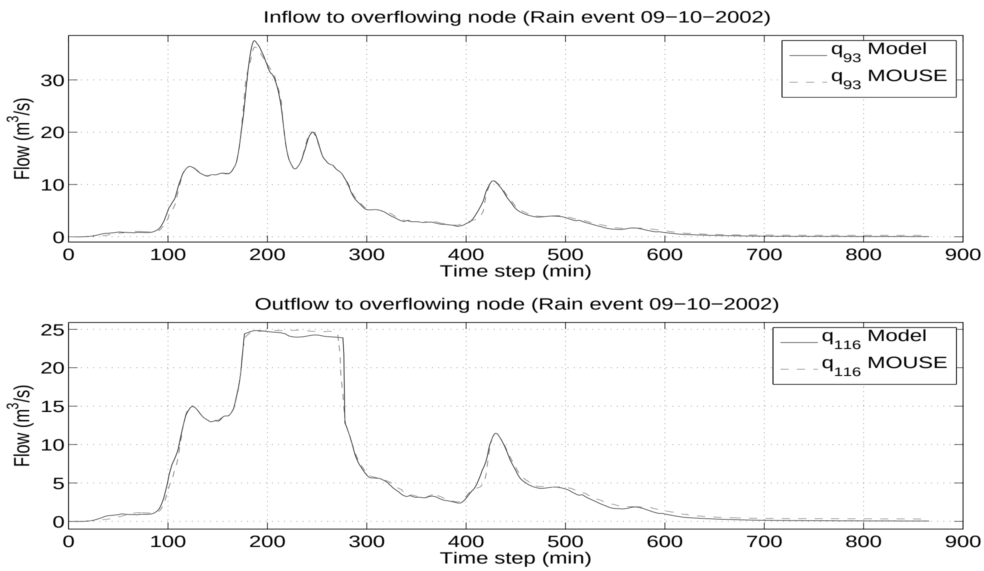

Figure 1: Inflow and outflow of an overflowing node as computed by MOUSE simulator and by the hybrid linear model.

To validate the model, the following expressions for the error have been used. For each sewer define $\bar{e}_i,\ i = 1 \dots n_q$, as the mean value of the accumulated absolute error over the simulation horizon H

$$\bar{e}_i = \frac{\sum_{t=1}^{H} |q_i^{in}(t) - \hat{q}_i^{in}(t)|}{H},$$

where q_i^{in} are the flows as computed by the model and $\hat{q}_i^{in}$ as computed by MOUSE. To obtain a description of the overall network behaviour, the mean and the maximum of these errors are used as indicators $E_1 = \frac{1}{n_q}\sum_{i=1}^{n_q} \bar{e}_i$ and $E_2 = \max_i \bar{e}_i$. The first part of Table 1 shows the results obtained for four real-rain events together with its duration H in 1-minute time steps.

Table 1: Simulation and RHC results

	Simulation Results			RHC Results		
Episode	E_1	E_2	H	Flooding [10^3m^3]	CSO [10^3m^3]	WWTP [10^3m^3]
17-09-2002	0.070	0.780	635	0.43 (-88.37%)	32.34 (-67.41%)	106.87 (75.24%)
09-10-2002	0.095	0.983	866	10.28 (-60.07%)	343.23 (-31.26%)	100.73 (19.74%)
15-08-2006	0.088	1.053	541	0.35 (-95.02%)	15.48 (-82.81%)	86.92 (87.46%)
30-07-2011	0.088	1.047	557	2.36 (-87.20%)	56.53 (-61.03%)	107.46 (124.06%)

RECEDING HORIZON CONTROL RESULTS

The Hybrid Linear Delayed System from (1) is shown to be easily adapted to formulate an Optimal Control Problem (OCP) to minimize overflows to the street and CSO discharges and to maximize wastewater treatmen plant (WWTP) usage thorugh the management of the gates present in the network. Given a rainfall prediction of H time steps in the future, the model can be extended to predict the network behaviour not only at the current time step but also at H steps ahead. Solving consecutive OCPs with this prediction horizon and updating flow values from simulator data give rise the well-known *receding horizon control* (RHC) strategy. By extending the vector of system variables to include the gate flows (thus letting them take free values between physical limits), the corresponding CSP can be turned into an optimization problem. This problem computes the optimal gate flow values that minimize an objective function that quantifies achievement of the previously mentioned control goals. These values are used as PID setpoints for local controllers implemented in the simulator.

The overflow volumes obtained when using the RHC strategy are shown to be notably inferior than those obtained by the passive control implemented in the simulator, as shown in the second part of Table 1.

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REFERENCES

[1] M. Schütze, A. Campisano, H. Colas, W. Schilling, and P. Vanrolleghem, “Real time control of urban wastewater systems - where do we stand today?”, *Journal of Hydrology*, vol. 299, no. 3–4, pp. 335–348, 2004.

[2] M. Gelormino and N. Ricker, “Model-predictive control of a combined sewer system”, *Int. J. Control*, vol. 59, no. 3, pp. 793–816, 1994.

[3] M. Marinaki and M. Papageorgiou, *Optimal Real-time Control of Sewer Networks*. London: Springer, 2005.

[4] G. Cembrano, J. Quevedo, M. Salamero, V. Puig, J. Figueras, and J. Mart, “Optimal control of urban drainage systems. A case study”, *Control Engineering Practice*, vol. 12, no. 1, pp. 1–9, 2004.

[5] C. Ocampo-Martinez, *Model predictive control of wastewater systems*. Advances in industrial control, London: Springer, 2011.

[6] A. Bemporad and M. Morari, “Control of systems integrating logic, dynamics, and constraints”, *Automatica*, vol. 35, no. 3, pp. 407–427, 1999.

[7] L. Jaulin, M. Kieffer, O. Didrit, and E. Walter, *Applied Interval Analysis*. Computational Intelligence and Complexity, London: Springer-Verlag, 2001.

[8] DHI Software, *MOUSE User Guide*, 2007.