A Feedback Simulation Procedure for Real-time Control of Urban Drainage Systems

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Abstract: This paper presents a feedback simulation procedure for the real-time control (RTC) of urban drainage systems (UDS) with the aim of providing accurate state evolutions to the RTC optimizer as well as illustrating the optimization performance in a virtual reality. Model predictive control (MPC) has been implemented to generate optimal solutions for the multiple objectives of UDS using a simplified conceptual model. A high-fidelity simulator InfoWorks ICM is used to carry on the simulation based on a high level detailed model of a UDS. Communication between optimizer and simulator is realized in a feedback manner, from which both the state dynamics and the optimal solutions have been implemented through realistic demonstrations. In order to validate the proposed procedure, a real pilot based on Badalona UDS has been applied as the case study.

Keywords: RTC, UDS, feedback simulation procedure, high-fidelity simulator, MPC.

1. INTRODUCTION

Urban drainage systems (UDS), which convey wastewater as well as stormwater to be treated before being released to the environment, are critical infrastructures with social, environmental and economic impact for the modern society, as discussed in Lund et al. (2018) and Garcia-Gutierrez et al. (2014). Due to the growth of urban population and the increasingly global warming effect in the last decades, as well as the high quality standard requirement for the water ecosystem defined by the EU Water Framework Directive (WFD, 2000/60/EC) as defined in Changing (2013), efficient management of UDS is required to achieve better performance by maximizing usage of the existing infrastructure and minimizing the pollution.

Real-time control (RTC) has attracted the attention of the UDS operators since 1970s, as described in Ackers and White (1973); Norreys and Cluckie (1997); Schilling (1989). With the recently fast development of the information, computation and communication techniques, the methodologies RTC have been widely and successfully used to improve the performance of UDS from both academia and industrial perspectives, as presented in Cembrano et al. (2004); Butler and Schüze (2005); Fu et al. (2008, 2010); Puig et al. (2009); Beeneken et al. (2013); Joseph-Duran et al. (2014a, 2014b, 2015); Sun et al. (2017b, 2018a, 2018b). As discussed in Garcia-Gutierrez et al. (2014), the RTC of UDS are multi-variable and multi-objective control problems combined with operational constraints, stochastic disturbances, as well as both continuous and discrete control elements, which adds a lot of complexities to the RTC implementation. Moreover, the hydraulic and hydrology dynamics of UDS are also very complicated with plenty of nonlinear and differential equations which produce potential risks of infeasible and non-convex problems to the optimization process as explained in Sun et al. (2017a); Garcia-Gutierrez et al. (2014). In order to implement RTC correctly and efficiently as required by the realistic online implementation, simplified conceptual modelling approaches are better choice to represent the main dynamics of UDS in RTC optimizer.

A high-fidelity simulator, as mentioned in Lund et al. (2018), is a platform which combines the most advanced modelling approach to replicate reality with high level of details in a single application with one simulation engine. Besides representing the detailed model of UDS, the simulator can also work with configuring and implementing simple control rules. But the limitation of not being able to consider external information and integrating optimization algorithms prevent the simulators from being a direct RTC optimizer.

In order to minimize the effect of model simplified by the conceptual models representation of UDS, this paper proposes a feedback simulation procedure to coordinate with the RTC optimizer using real-time realistic state updated by a simulator. Furthermore, the performance of the optimal solutions produced by RTC optimizer can be illustrated in virtual reality through the simulator without affecting the operation of real systems. Model predictive control (MPC), as explained in Mayne (2014) and applied in Sun et al. (2013, 2015, 2014a, 2014b, 2016, 2017c) and Ocampo-Martínez et al. (2013), has been selected as the main control method to generate optimal solutions for the multiple objectives of UDS. InfoWorks ICM, described in MWH (2010), is used to carry out the virtual reality simulation, acting as the UDS detailed model.

The remaining part of this paper is organized as follows: In Section 2, the RTC optimizer, the UDS simulator, as well as the feedback simulation procedure are defined. In Section 3, to validate the proposed procedures, a real life pilot, Badalona UDS, is used as case study. Implementation results are presented in Section 4. Conclusions as well as the future working plan are discussed in Section 5.

2. METHODOLOGIES

2.1 MPC based Optimizer

Model predictive control involves an optimizer which can produce optimal control actions $\boldsymbol{Z}$ in a horizon $\boldsymbol{K}$ (normally 30 minutes) through minimizing the given cost function $\boldsymbol{J}$ under a UDS mathematical model and operational constraints.

In order to obtain the control actions efficiently using small computing load, simplified conceptual models are used to represent both hydraulic and hydrology dynamics of UDS using simple mathematical equations. Details about the conceptual modelling approach can be found in Sun et al, (2017a) and Joseph-Duran (2014b).

Objectives of UDS focus on minimizing the pollution effects to the water ecosystems, especially in storm weather, through minimizing CSO (combined sewer overflow) and the released pollutants, as well as maximizing the usage of existed UDS infrastructures, such as, the detention tank, and the WWTP (wastewater treatment plant), etc., as shown in equation (1):

$$J(x,u,w) = a_{cso}J_{cso} + a_{wwtp}J_{wwtp} + a_{safe}J_{safe} + a_{smoothness}J_{smoothness} + a_{Mass}J_{Mass} \quad (1)$$

The weights a_{cso}, a_{wwtp}, a_{safe}, $a_{smoothness}$, a_{Mass} are defined taking into account their prioritization. More descriptions about the objective functions can be referred in Sun et al. (2017b, 2018a, 2018b).

The optimization problem based on MPC can be presented in a quadratic optimization problem as represented in Sun et al. (2015, 2018a). A brief description is:

$$\min_{\boldsymbol{x},\boldsymbol{u}} J(\boldsymbol{x},\boldsymbol{u},\boldsymbol{w})$$

$$s.t. \qquad x(t) = x_0,$$

$$x(k+1) = f\big(x(k),u(k),w(k)\big), \quad k = t,\dots,t+H,$$

$$h\big(x(k),u(k),w(k)\big) \le 0, \quad k = t,\dots,t+H, \qquad (2)$$

$$x_{min} \le x(k) \le x_{max}, \quad k = t,\dots,t+H,$$
$$u_{min} \le u(k) \le u_{max}, \quad k = t,\dots,t+H.$$

where $\boldsymbol{x}(t)$ is the sequence of system states representing water volume in tanks and the TSS mass; $\boldsymbol{u}(t)$ is the sequence of control actions for a commanded gate; $\boldsymbol{w}(t)$ is the sequence of disturbances related to rain intensity and runoff. $\boldsymbol{u}_{\boldsymbol{min}}$, u_{max}, x_{min}, x_{max}, are their physical limits.

This MPC-based RTC solution is computed through the General Algebraic Modelling System (GAMS) optimization engine, as explained in Rosenthal (2016) using the CONOPT3 optimization algorithm.

2.2 Simulation using InfoWorks ICM

InfoWorks ICM is a simulation platform that incorporates detailed and accurate physical models about hydraulic and quality dynamics for the sewer networks, including active and passive elements behaviour (links, nodes, pumps, gates…).

Besides using the GUI, an API in Ruby language, InfoWorks ICM Exchange, is the employed method for the communication with the RTC module. This API can define, configure and execute a simulation through Ruby programming. Furthermore, by means of a Ruby environment, applications of other software like GAMS optimizer can be integrated through user-defined classes, objects and interfaces.

In this paper, InfoWorks ICM Exchange is used to define a simulation, where the network model, rain time-series, quality parameters, hotstart files, etc. are configured at beginning of the software running.

The inputs parameters like simulation start time and data, duration of the simulation as well as the control settings can also be parameterized using the Exchange API, and updated at every simulation step.

2.3 Feedback Simulation Procedure

The feedback simulation procedure is proposed to coordinate the MPC-based RTC optimizer with the sewer network detailed model in order to guarantee that the detailed dynamics of UDS, which is described through the simulation model, can be taken into account into the optimization process. As presented in Fig 1, the procedure is working in an interactively way through coordinating information between the RTC optimizer and the simulator.

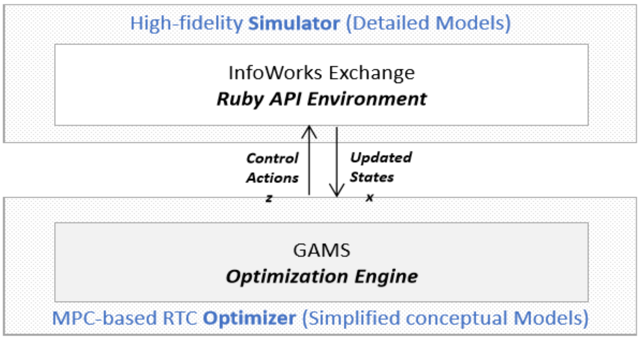

Fig. 1. Feedback simulation procedure.

In each control iteration, the MPC-based RTC optimizer computes optimal actuator actions $\boldsymbol{Z}$ (mainly for the actuators like pumps, gates, etc.) through GAMS optimization library using simplified conceptual model and forecasted disturbances of UDS. The control actions are then sent to the simulator through Ruby API, which works with detailed models as virtual reality. After implementing the simulation using optimal control set-points, specified measurements of state variables $\boldsymbol{X}$ (mainly detention tank volume, rainfall inputs, etc.) are retrieved from simulator to capture the effect of the control actions, and these are sent as initial states back to the RTC optimizer for the next interval.

The simulator provides the start point for the feedback loop, which needs initial configuration to produce the states values as initial input for the optimizer. In order to have consistent results, similar sampling steps are used in both the optimizer and simulator.

3. CASE STUDY

The case study is a real pilot based on the UDS of Badalona, which is the third most-populated municipality in Catalonia and locates besides the Mediterranean Sea.

Regarding environmental issues, Badalona presents several kilometers of beaches with a significant impact on the tourism of the city. During extreme rain events, part of stormwater may not be admitted into WWTPs, generating CSOs with significant environmental, social and economic damage related to the quality of bathing waters.

The sewer network is mostly a combined system, all the mixed sewage are collected and conveyed together into the WWTP for treatment. Treated water is conveyed to the Mediterranean Sea through a marine outfall. The main actuation element in this network is the retention tank, designed to serve as a flooding prevention structure, as well as a retaining element for highly polluted runoff from the city surface.

3.1 MPC based Optimizer

The simplified conceptual model of the Badalona UDS, represented by the equations the optimizer employs during its operation, is depicted in Fig. 3. These equations are implemented in the GAMS code files, together with the variables and equations declarations for the proper function.

Regarding the needed input information, the GAMS model is fed at each iteration with the hydraulic (flow) and quality (TSS) data of the corresponding time instant, as well as the future time instants comprised in the optimization horizon, at every Virtual Tank (VT) of the simplified network. These Virtual Tanks, which are illustrated in Fig. 3, are employed to represent the water coming from different areas of the detailed network, so that the simplified model considers them as flow and TSS inputs, highly reducing the complexity of the optimization operation. Therefore, this information is provided from external results files, as information of future time instants is necessary for the optimization process.

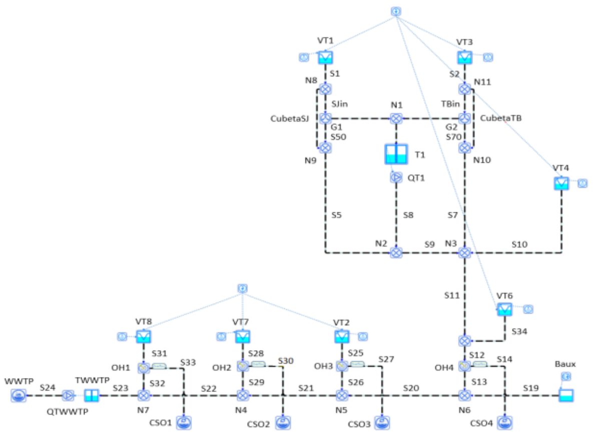

Fig. 3. Badalona pilot simplified model

Besides these VTs, there exists another fictitious tank in the simplified model entitled as TWWTP, which accumulates the water coming to the WWTP before it is pumped. This tank represents a complex sewer structure located at the end of the real network, so that the overflow of the container models the nearest CSO to the WWTP, while the accumulated water in the tank corresponds indeed to collected liquid in the pumping station.

The Estrella tank is modelled by the T1 tank, and both its volume as well as the volume of TWWTP are provided to GAMS as initial values: the first is obtained from the current simulation, and the second from the previous optimization. Other equally initialized variables are the TSS at the output sewer of the tank T1 or its accumulated mass, supplied from the previous optimization too; and the WWTP nearest CSO flow, that is provided from the actual virtual reality.

Besides, due to the non-linearities introduced by the multiplication of flows and TSSs, the flow forecast from the previous optimization is extracted and provided to the next one, just for the quality-related equations.

Once the optimization is carried out, the actuators operation for the next simulation is obtained by converting certain flows to setpoints. Concretely, for the Badalona UDS, the different actuators are the position of the gates G1 and G2, which are divided into G11, G12, G21 and G22 (G11 and G21 connect the input sewer with the tank, while G12 and G22 connect with the rest of the network; but the sum of the positions of G11 with G12 and G21 with G22 are constants); together with the number of pumps operating to empty the tank T1 (at the detailed network, this element is modelled as a single pump (P1) that can operate in three different modes).

The flows employed for the conversion are: S3 for G11, S50 for G12, S4 for G21, S70 for G22 and S8 for P1.

3.2 Simulation using InfoWorks ICM

The detailed model simulator serves as a virtual reality of the Badalona UDS in order to obtain the necessary feedback to complete the CLSA (closed-loop simulation algorithm). The selection of this concrete software stems from the decision of the operators that manage the real Badalona network, considering it a sufficiently accurate simulator to provide proper data and results for the control loop.

The software can be configured both from the GUI as well as from the Ruby API. One of the most important configurable elements consists of the possibility of supplying the control regulator setpoints for the actuators from a Regulator object.

For the Badalona UDS case, as described in the previous section, five setpoints need to be provided to the simulator by means of this Regulator object, so that during the simulation at the next iteration of the loop, the different actuators (G11, G12, G21, G22 and P1) behave as the optimizer computed.

Other important configuration factors are the episode settings, specified by the selection of the simulation starting date and time and the rain event (coming from a database with different rain profiles for the distinct years); the coldstart data to prepare the network for the desired simulation; and several parametric values, highlighting the build-up time (number of hours from the end of the previous rain episode to the current simulation start), timestep, duration, units, etc.

At the end of each simulation, the results are provided by InfoWorks ICM in the form of .CSV. The most significant results are the flows, TSSs, depths, sediments depths and velocities, at both the downstream and upstream of each sewer; the volumes of the links and nodes and the regulator states.

3.3 Feedback Simulation Procedure

As aforementioned, the selected environment to integrate the two presented software elements is a Ruby script, so that it is the responsible of implementing the CLSA, allowing the communication between the modules of the system.

Regarding the Ruby management of the detailed model operation, all the configuration settings are carried out by means of the InfoWorks Exchange API. The resulting CSV files for each simulation are read, the data is extracted and then stored in another CSV file, common for all the iterations. Therefore, once the closed-loop operation is finished, every iteration results are available at this CSV file.

About the processes related to the GAMS optimization, there exist several text edition routines programmed in a Ruby library, regarding tasks like preparing the initial conditions and VTs inputs files from the flow and TSS optimizer and detailed model results; generating the flow forecast file from the previous optimization results, running GAMS from the command-line, converting the optimization resultant flows to setpoint positions and creating the regulators file, which can be used by means of the API to configure the simulator regulator for the next iteration. Therefore, the loop regarding the RTC controller and the UDS simulator is closed.

It is worth to mention the third needed element for a complete integration: the WWTP simulator. GPS-X 6.5.1 is employed for this task, and its configuration, operation and results storage is also managed from the Ruby environment. However, for the purposes of this paper, these processes features are not further explained.

A schematic diagram representing the CLSA operation is depicted in Fig. 4.

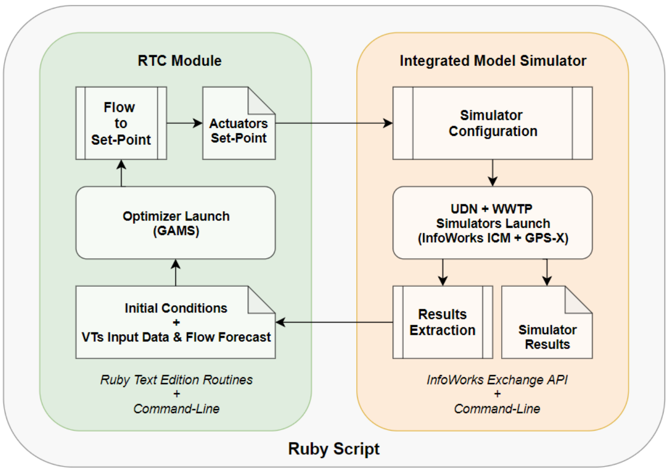

Fig. 4. Structure of the overall CLSA for the Badalona pilot.

4. RESULTS

In order to prove the proper behaviour of the developed methodology applied to the presented case study, the rain episode of the 20th of April of 2016 has been selected (due to its medium-high rain profile and common usage during the development of this methodology) to get some results.

In Figures from 5 to 7, the GAMS optimized flows at each iteration of the simulation are depicted along with the CLSA detailed model actual flows, for the Badalona simplified network most interesting links: S3, S4 and S8 (S50 and S70 are not depicted due to their low importance in this scenario). As mentioned, the first two links correspond to the sewers that act as inputs to the tank T1, and the last link corresponds to the output of that tank. The time step for both the simulation and optimization at each figure cover 5 minutes, but a distinct x-axis gridding is used to improve the graphics understanding, standing out the proper functioning of the CLSA.

The figures show how the optimizer resultant flows, employed for their conversion to set-points for the virtual reality, shape the actual flows of the detailed model simulator as expected. Therefore, the different plots show the direct impact of the optimization results in the detailed model, as the control rules that manage the detailed model actuators are derived from optimized values.

On the one hand, for the case of the gates G1 and G2 at Fig. 5 and Fig. 6, the similarity between the GAMS optimized flow entering the retention tank and its actual inflow at the detailed model simulation clearly illustrates the achievement of the main objective.

On the other hand, the difference between the two plots in Fig. 7 stems from the flow limits that produce the activation or deactivation of the pumps. As aforementioned, the detailed model pump only works pumping in four actuation modes: off (0 m^3/s), 0.33 m^3/s, 0.66 m^3/s and 1 m^3/s. However, the optimizer can reach any value from 0 m^3/s to 1 m^3/s. Hence, the VR pump modes are only activated when the corresponding flow is reached in GAMS.

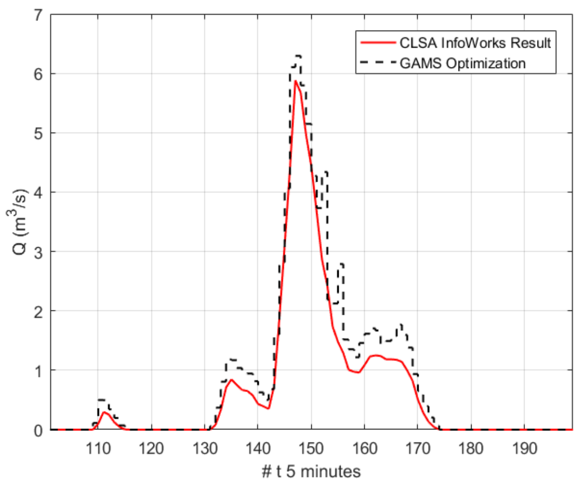

Fig. 5. Detailed model and optimizer flows of S3.

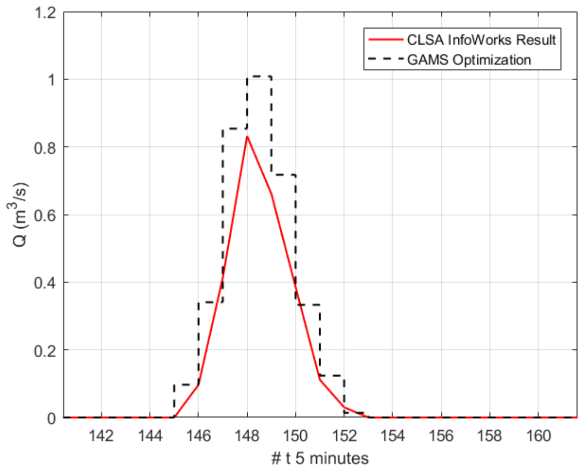

Fig. 6. Detailed model and optimizer flows of S4..

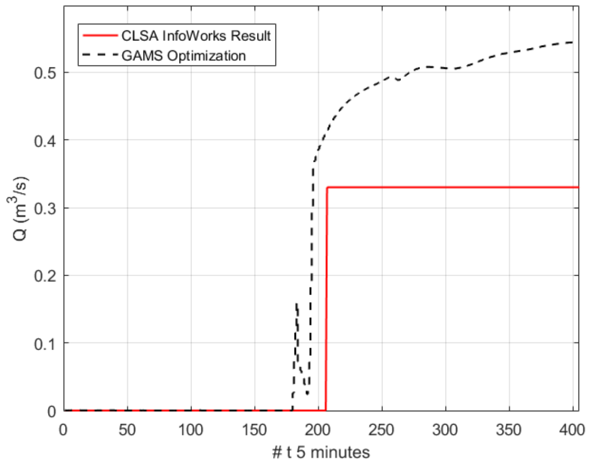

Fig. 7. Detailed model and optimizer flows of S8.

To complete the assessment of the MPC approach closed-loop structure, some performance results for the presented rain episode are included in Table 1. They represent the total spilled volume and mass at the optimization process considered CSO points (only two are included because the rest of them are completely passive and independent on the control strategy). As presented, an important improvement is achieved by means of the implementation of the MPC approach at both the spilled volume and mass.

	Local Control	**MPC**
CSO Volume	64780.437 m^3	53493.366 m^3
% Reduction	-	17.42 %
CSO Mass	14456.991 kg	13460.786 kg
% Reduction	-	6.89 %

Table 1. CSO performance results

5. CONCLUSIONS

With the aim of providing accurate state evolutions to the RTC optimizer and illustrating the optimization performance in a virtual reality, a feedback simulation procedure for the RTC of UDS is presented in this paper. MPC with simplified conceptual quantity and quality models has been used to compute optimal solutions for the multiple objectives. InfoWorks ICM is used to carry on the simulation in a virtual reality. A feedback procedure using Ruby script has been designed to realize the communication between optimizer and simulator, from which both the realistic state dynamics and the optimal solutions have been implemented through realistic demonstrations. The behaviour and function of the proposed approaches have been validated using a real life pilot Badalona UDS in a rain episode of 20th of April of 2016 in the Sections 3 and 4, which confirms that, the updated simulation states have been implemented into the optimizer in each iteration, while the control set-points produced by the RTC optimizer indeed behaves into the simulator in an expected way.

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