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MODEL PREDICTIVE CONTROL COMBINED WITH GENETIC ALGORITHMS FOR A RIVER SYSTEM

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Real time flood control becomes more widely applied given its features to make more efficient use of existing storage capacity available in flood control reservoirs. In order to accelerate the large number of iterations concerning the hydraulic computations in optimization procedures, a simplified river conceptual model was developed and connected to a Model Predictive Control (MPC) algorithm. This tool was applied to determine efficient real-time flood control policies for the 12 gated-weirs in the Belgian case study of the river Demer around two main flood control reservoirs. Because the system dynamics are nonlinear (gate openings are considered as inputs in the MPC), the MPC was combined with Genetic Algorithms (GAs) to cope with the nonlinear problems. The MPCGA model searches for better control actions by minimizing the cost function while at the same time avoiding violation of the defined constraints. The optimization results testify that MPCGA is capable of improving the current regulation strategy that is based on fixed regulation rules and three-point controllers.

INTRODUCTION

Flood is one of the most universal and pricey natural disasters around the world. For Europe, the European Commission published in 2007 the EU Flood Directive to develop flood risk management plans (with focus on prevention, protection and preparedness) in connection with river basin management plans (for river basins and associated coastal areas at flood risk). In these plans, appropriate measures have to be considered to reduce the risk of flooding. When Belgium is taken as an example of a Western European country, flooding was the most people-affected natural hazard and occupied the largest proportion of the top ten of natural disasters (seven of ten) during the period between 1900 and 2013.

Given that floods may lead to severe damages, how to perform an effective flood control is of major interest to governments and water authorities. Furthermore, the flood risk is expected to drastically increase during the coming decades due to the rising impacts of increasing urbanization and global climate change. There is a growing need for water managers to efficiently cope with these trends.

The research presented in this paper investigates the possibility and efficiency of real-time optimal control on the hydraulic structures and flood control reservoirs in a river basin in order to limit river flooding. The river Demer case in Belgium is taken as case study.

In order to establish successful flood control strategies to prevent or alleviate flood damages, developing a suitable river flood model is a must. For this research, the conceptual river model is built-up to concisely describe the dynamics of the river system with high accuracy (similar or close to a detailed full hydrodynamic InfoWorks RS model) at fast speed. This model aims at searching for better gate-operation policies for the flood event through large number of iterations, which are run by an optimization model. The research is also to develop a procedure for the real-time optimal control of the hydraulic structures. This requires comprehending the whole procedure for such control, making use of the technique of Model Predictive Control (MPC) and learning how to link it with the conceptual model. In addition to the MPC algorithm, an adequate MPC-based optimization technique needs to be selected, which can cope with nonlinear dynamics of the process model such as optimizing openings of the hydraulic structures (e.g. gated weirs) of the assigned study area in real time at each sampling instant (e.g. 5 minutes).

The principle objective of this research is to be able to carry out real-time flood control by connecting the conceptual hydrologic-hydraulic model with the nonlinear MPC (NMPC) optimized by an optimization technique. A concrete procedure for real time flood control is built up. The results are evaluated by comparing with the current regulation strategy and by how much the real time control procedure mitigates negative/harmful flood conditions of the study area.

THE DEMER RIVER SYSTEM

The Demer river system

The Flanders region of Belgium is composed of eleven river basins. The river Demer basin is one of them. It is located in the eastern part of Belgium with an area of 2,276 km^2. The river Demer has a total length of 85 km. The main land use types covering the catchment are cultivable land (41%), forest (22%), urban area (19%), pasture (15%) and wetlands and water bodies (3%) [1].

The lowland (low-lying) river Demer basin suffered in the recent past from several severe flood problems. This is because this basin rapidly responds to the catchment precipitation and high river flows frequently occur after heavy and long rainfalls. Therefore, the river Demer has its history to be viewed as a definite case for discussing flood problems. In the past, flooding along this river could not be prevented during several periods of heavy rainfall events. Taking five major recent historical flood events (December 1993, January 1995, September 1998, February 2002 and December 2002-January2003) for example, they respectively caused 23.5, 22.9, 32.6, 15.7 and 18.0 km^2 estimated flood area and huge economical losses in the Demer basin. Especially in September 1998, the flood disaster led to a loss of 16,169,000 Euros [2].

In order to alleviate such flood disasters, the Flemish Environment Agency (Vlaamse Milieumaatschappij, VMM), installed hydraulic facilities (e.g. movable gated weirs) along the rivers. Several flood-control reservoirs are to provide storage for the excess volume of water. Two of the largest ones are called Schulensmeer and Webbekom. Structures which control the flows towards or out of the available reservoirs are regulated by the operating rules formulated by the VMM water authority. Through the implementation of the two reservoirs and hydraulic structures, the water authority is able to dominate or reduce the majority of flooding caused by non-extremely heavy rainfall events. However, it obviously cannot fully avoid extreme flood events. A more advanced control strategy would be useful. In order to establish successful flood control strategies to prevent or alleviate flood damages, besides setting operating rules (regulations) for the hydraulic structures, real time optimization-based control can be a supplementary strategy for water managers. This research investigated such real time flood control option and discusses its potential efficiency for this particular river system.

Conceptualization procedure for the river system

Concerning the hydraulic river models implemented in this research, a detailed full hydrodynamic model, InfoWorks-RS model, was applied in conducting detailed hydrodynamic simulations of the river network. It simulates the detailed physically-based hydrodynamic processes for open channels, floodplains, embankments and hydraulic structures. One of the main problems to date is that existing full hydrodynamic models have very long computational time. They therefore cannot be directly applied in real-time control employing optimization because of a huge number of model iterations needed. However, conceptual models can resolve this problem. By means of the simulation results of the full hydrodynamic river model, a conceptual river model can be well identified, calibrated and built in order to employ its computational accuracy and efficiency for the optimization of the real-time flood control.

An important step of building a conceptual river model is to schematize the study area by only selecting the representative discharges, storage points and hydraulic structures to compose a simplified river network. Figure 1 shows the schematization of a part of the Demer basin by means of a system diagram that only covers the Schulensmeer and Webbekom reservoirs.

These simplified representations are used to build the model and measurements (e.g. river flow and water level time series at gauging stations) for calibration. The density of river gauging stations to calibrate conceptual model is, however, most often very limited. The conceptual model structure can be equally well identified and calibrated based on the simulation results of the full hydrodynamic river model. Therefore, it allows to quickly obtain system responses in different flow conditions and to strongly reduce the calculation time. This is very useful in applications of optimization of flood control strategies. For details on the calibration process, the evaluations of the performance (accuracy and calculation time) and robustness of the conceptual model, the reader is referred to [3].

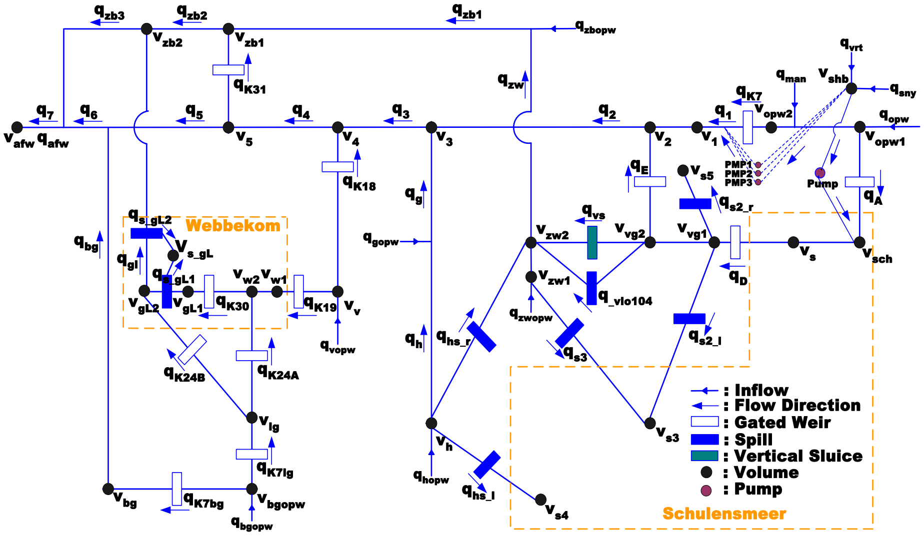


Figure 1. Schematic overview of the conceptual model structure for the study area

MODEL PREDICTIVE CONTROL WITH GENETIC ALGORITHM FOR REAL-TIME FLOOD CONTROL

Model predictive control (MPC)

Model Predictive Control (MPC), called Receding Horizon Control (RHC), is a class of control methods that utilize explicit process descriptions to predict the future response of a system and steer a system to a desired output using optimization as an intermediate step [4]. MPC does not refer to a specific control strategy. Instead, it refers to a broad range of control methods that use a process model of the real system to obtain an optimal sequence of control actions by minimizing an objective function [5]. Typically a quadratic cost function is applied that evaluates the difference between the reference signal and the predicted process output in a given future horizon. From the calculated control signal series, only the first time step value is applied as input to the process model and at the next time steps the calculation is repeated. The control action is based by looking ahead for N steps and evaluates the efficiency of the control action by means of a given objective or cost function. The optimized control action is only implemented for the first time step. At the next time step, an adjusted control action is made by taking updated information into account and looking ahead for another N steps. This is called a receding horizon strategy and is also the concept of MPC. In addition, MPC is also an optimization-based control paradigm and composed of feedback, feedforward and optimal controllers and can handle system constraints on inputs and states and also optimize the sequence of control actions. The feedback control part is by considering measurements and current states. The feedforward control part is by utilizing predicted disturbances (e.g. rainfall or catchment runoff or upstream river flows). The MPC aims to determine faster and smoother operations. Barjas Blanco [6] made an clear and concise description of MPC when implemented to open water systems. He concluded that MPC is very promising in determining control actions making use of water levels predictions based on rainfall forecasts.

The objective function (called cost function) implemented in this research for the MPC optimization aims to lighten the flood damage. The function includes the damage cost caused by excessive water over the desired water levels (flooding) and the gates' operation cost. Then, the model is used to search for the best operating policy (gate-openings) to minimize the total cost. The damage cost and operation cost are individually defined by the two terms of Eq (1). The control horizon is assumed to be equal to the prediction horizon.

$$J = \sum_{i=1}^{m} W1_i \sum_{j=1}^{N_c} [\hat{y}_i(k+j) - r_i(k+j)]^2 + \sum_{i=1}^{n} W2_i \sum_{j=1}^{N_c} [\Delta u_i(k+j-1)]^2 \qquad (1)$$

The cost function is, subject to the two following constraints presented in Eqs (2) and (3),

$$\underline{y_i} \le \hat{y}_i(k+j) \le \overline{y_i}\text{ , for } i = 1\ldots m,\ j = 1\ldots N_c \qquad (2)$$

$$\Delta u_i(k+j-1) \le \Delta u_{i,\max}\text{ , for } i = 1\ldots n,\ j = 1\ldots N_c \qquad (3)$$

where m is the number of selected water levels to be observed, $W1_i$ the weighting factor for the selected water level i, N_c the control horizon, $\hat{y}_i$ the future water level i, r_i the desired water level i, k *and* j the current and future time steps, n the number of gated weirs in the system, $W2_i$ the weighting factor for the gated weir i, Δu_i the movement for the gated weir i, $\underline{y_i}$ and $\overline{y_i}$ the lower and upper limits of the future water level *i*, $\Delta u_{i,\max}$ the maximum allowable movement for the gated weir *i* within a time step.

When the model optimizes a new operating policy for determining new gate openings, the latest outputs (20 selected water levels) are immediately generated by the river model. Then, every water level gets its damage severity by judging which zone of damage severity the water is located in. Four zones are defined, based on the target level during normal conditions, the flood warning level, the flood alarm level and the real flood level. For instance, when the water is above warning level, it is in the second zone and its damage severity is 2. The bigger damage severity generates larger weighting factor for the water level. The weighting factor ($W1_{i,k}$) of the selected water level i (i=1,…20) in every zone (k=1,...4) for Eq. (1) is described in Eq. (4)

$$W1_{i,k} = (PH_{i,k})^2 * (10.0)^{DS_{i,k}} \tag{4}$$

where $PH_{i,k}$ is the water level percentage according to the relative position of the water level *i* in the range of water levels covered by the zone *k*, $DS_{i,k}$ the “damage severity” for the selected water level *i* in the zone *k* when this water level is above its corresponding desired level. The weighting factor ($W2_i$) for the gated weir *i* is generated by comparing the “weighting factors” and “damage severities” of the up- and downstream water levels of the gated weir *i* to avoid generating too large gate openings between two time steps through the computation of the operation cost.

MPC combined with Genetic Algorithm (GA) for the real-time flood control

An optimization model or technique is employed to search in MPC at each time step for the most effective solution for the control action, among many other candidate solutions. It also should take into account constrains, which place limitations on the decision. Given that real time flood control requires gate operations based on nonlinear gate equations (depending on the up- and downstream water levels of the gate), the nonlinear dynamics of the process model have to be taken into account. How to choose an adequate optimization algorithm for MPC under such highly nonlinear process systems is an important issue. In addition, a potential optimization technique must have the ability to handle constrained, nonlinear and non-convex problems and to find the global optimum.

In this research, to overcome the problems related to the strong nonlinear dynamics of the river system during flood events, in combination with the system constraints, the nonlinear MPC (NMPC) was selected, combined with a binary-coded standard/simple GA (SGA) as optimizer (due to its maturity and accessibility) and to make the complicated NMPC computation process easier. This model predictive controller combined with GA is hereafter referred to as MPCGA. Although GA makes it easier to conduct optimization computations for a nonlinear system, one important weakness is its high computational cost. It could be improved by a fast and accurate river conceptual model we developed for the Demer case.

GA’s Encoding for MPC

In this research, a chromosome (or called an individual) of GA is composed of movements of all the gated weirs (12 gates) within the control horizon N_c (we assumed prediction horizon $N_p = N_c = 48$ hours). It means the 12 gate movements of the first hour were constructed in the first twelve genes of an individual; the 12 gate movements of the second hour would be sequentially located in the 13th to 24th genes.

Every gene in a chromosome represents a change Δu in the control action, where the sequence of the genes in the chromosome provides the corresponding future change information. For example, at time step k, the first gene in the chromosome is encoded to the change in the control action $\Delta u(k)$ that is added to $u(k-1)$, to obtain the control action $u(k)$. In other words, when all genes in the chromosome are decoded, the control trajectory (a series of future control signals, $u(k + j)$ for $j = 0,\ldots, H_c-1$, where H_c is the control horizon) can be extracted. In this research, the genes (variables) are encoded as bit strings using a standard binary coding.

Figure 2 illustrates the relationship between a gene's searching range (optimal range) and its possible control action, where $u(j)$ denotes the control action at the time step j, u_{max} and u_{min} denote the maximum and minimum allowed control actions, Δu_+ and Δu_- denote the maximum positive and negative changes in the control actions. Using the same example mentioned above, firstly, the search space of a gene $\Delta u(j)$ is determined. There are two sources that can provide possible positive and negative changes for a control action: (1) Δu_+ and Δu_- , and (2) the difference between the previous control action $u(j-1)$ and u_{max} and u_{min}, respectively. The possible optimal range of a gene $\Delta u(j)$ is decided by the minimum of these two sources and then the optimal $u(j)$ is obtained based on this search space (shaded in Figure 2).

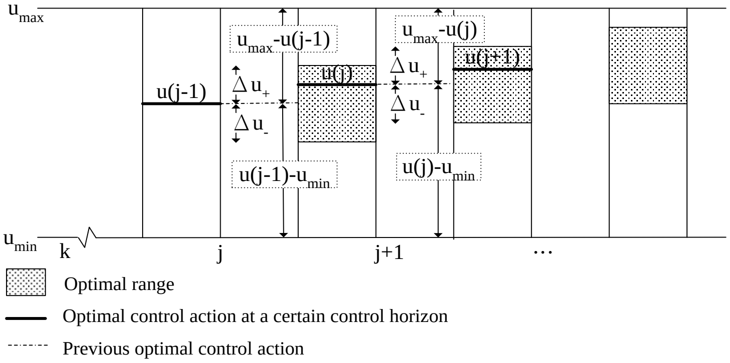


Figure 2. The relationship between a gene's search range and its possible control action

For determining a certain control action at time step $k+j-1$, $1 \le j \le H_c$ (j means the j^{th} gene), the maximum positive and negative changes from the previous control action $u(k+j-2)$ are obtained by Eqs (5) and (6) with a modification.

$$\Delta U_{\text{sup}}(j) = Round\left[\min(\Delta u_+, u_{\max} - u(k+j-2))/GM\right] \tag{5}$$

$$\Delta U_{\text{inf}}(j) = Round\left[\min(\Delta u_-, u(k+j-2) - u_{\min})/GM\right] \tag{6}$$

The gate moving speed GM is assumed fixed (obtained from operational restrictions). For that reason, the positive changes $\Delta U_{sup}(j)$ and negative changes $\Delta U_{inf}(j)$ are set as integer multiples of the gate moving speed. When a certain gene is decoded and mapped to get gate movement, the model will make this non-integer multiple become an integer value. Furthermore, every gene in the chromosome uses the most left bit for determining the moving direction of a gated weir (e.g. 1 for raising the gate and 0 for declining the gate) and the second left bit for determining if the gate moving will be executed (1 for executing gate moving and 0 for non-executing gate moving). The new control action will be computed by Eqs (7) or (8).

$$u_t = u_{t-1} + EGM * GM * Round(decoding/(2^n - 1) * \Delta U_{\sup}) \quad (7)$$

$$u_t = u_{t-1} - EGM * GM * Round(decoding/(2^n - 1) * \Delta U_{\inf}) \quad (8)$$

where *EGM* is an index indicating whether gate moving is executed: 1 for action, 0 for non-action. The control time step is 5 minutes, but the operation is repeated only once per hour. Therefore, the 5-minute movement of each gated weir is obtained from its hourly gate movement divided by 12.

TEST CASE

Model set-up

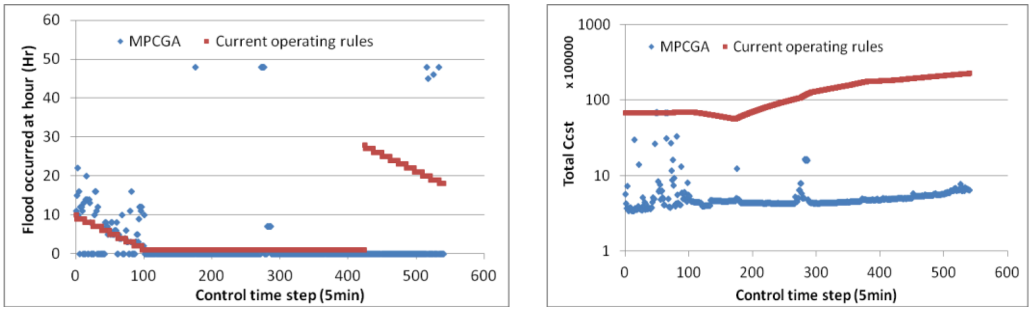
The 1998 flood event (03/09/10h00 ~ 01/10/12h00, 675 hours) was selected as the primary test case because of its severe inundation conditions. The running period was set from 250 hours to 295 hours. The initial conditions of the whole system were obtained from the simulation of the current operating rules between hour 0 and 250. Related to the process disturbance, the research used catchment rainfall-runoff inflow discharges obtained by simulating historical rainfall data in conceptual rainfall-runoff models of the different subcatchments; hence assuming perfect rainfall forecasts.

Regarding the system constraints for the input and state variables, for each input variable its maximal gate movement at every time step follows the current operating rules. The state variables were restricted to their limits. In case one of these limits are exceeded, a large punishment is given in order to be eliminated in the next generation. To avoid that no good candidate solution is found because of this large punishment, one additional candidate solution will be added: based on the current (initial) hydraulic conditions that are gotten from the last time step optimized by MPCGA model (called half-rule operation). Then the model encodes these 48-hour gate movements to one randomly-selected chromosome (individual) when the optimization process reaches its convergence condition. However, even if the rule operation is used for the current time step, the best individual after rule operation is not kept for the next time step. Only the best individual before the rule operation is recorded and considered in the next time step to provide useful information. In order to check the performance of MPCGA model, the fitness of the MPCGA is compared with that after application of the current operating rules (called full-rule operation) and instantly presented for every time step.

Results and discussion

After application of the real time flood control by MPCGA as outlined above, to the Demer river system, it is shown that the important effect of the MPCGA is to make the water levels above their corresponding flood levels as delayed as possible during the period of the control horizon (48 hours). The best solution is the one where any water level below its flood level occurs within the control horizon. The worst solution is the one where the water level is above its flood level at hour =1; which means the flood will happen within the next hour or the flooding already started. Therefore, from the comparison of the 5-minutes results between the MPCGA and the current operating rules, the hour is derived and compared at which the flood starts (in the control horizon). Figure 3a shows that for the current operating rules the flood starts at hour = 9. After MPCGA control, that flood starting time becomes zero or delayed in comparison with the current operating rules. Besides delaying flood occurrence, another important effect of the real time control after MPCGA is a reduction in the total cost (damage +

operation costs); see Figure 3b. Note that the cost obtained after MPCGA is bound by the cost obtained after simulation of the current regulating rules because of the half-rule operation when the model cannot find a better (smaller) fitness than punishment as explained above.



a) b)

Figure 3. a) Comparison of MPCGA and current operating rules for the starting time (hour) of the flood in the control horizon and b) Comparion of total cost in the results after MPCGA and current operating rules

CONCLUSIONS

The paper presented a method for Model Predictive Control (MPC) combined with Genetic Algorithm (GA) for the real time flood control. After application to a Belgian river system, results show that the proposed control strategy is able to provide an advanced solution for flood control, hence to assist water managers in controlling the hydraulic structures. Future work will include the data assimilation on the rainfall-runoff inflow discharges and consideration of uncertainties in the system model and future rainfall forecasts.

ACKNOWLEDGEMENTS

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