

Adaptive and predictive control architecture of inland navigation networks in a global change context: application to the Cuinchy-Fontinettes reach ^{*}

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Abstract: In this paper, an adaptive and predictive control architecture is proposed to improve the management of inland navigation networks in a global change context. This architecture aims at ensuring the seaworthiness conditions of inland navigation networks, and to improve the efficiency of the water resource management. It is based on supervision and prognosis modules which allow the estimation of the current state of the network, and the forecasting of the extreme event occurrence. According to these indicators and to the management constraints and objectives, control strategies of the inland navigation networks will be adapted to limit the impacts of the extreme events. To achieve this aim, three challenges are considered and discussed in this paper. The first one consists in proposing an accurate modeling approach of navigation reaches which are characterized by large scale, nonlinearities, time delays, unknown inputs and outputs, etc. The second one is to increase the knowledge about potentiality of extreme events, consequences of the climate change. The prediction of these events is rather complex due to their rarity, the spacio-temporal scale of the networks, etc. Finally, the third one is the pooling of the two first contributions, *i.e.* the model of the system and the knowledge about extreme events. Thus, the resilience of the system and the adaptation of the management strategies could be realized.

Keywords: Adaptive control, Predictive control, Supervision, Prognosis, Large scale system, Navigation system

1. INTRODUCTION

Inland navigation networks in the north of Europe cover more than 42,000 km of canals, rivers and canalized rivers. They are used to transport goods from sea to the continent's urban and industrial centers. They provide economic and environmental benefits (Mihic2011; Mallidis2012) by allowing an efficient, quieter, and safer transport of goods (Brand 2012). To promote this transport mode as alternative to land transport, infrastructures were built to accommodate large broad gauge boats with an increasing of the navigation schedules. It is the case in the North of France with the construction of the Seine-Nord canal. Moreover, benefiting of the progress on Information and Communication Technology (ICT), new sensors and actuators are implemented on the navigation reaches (Ten Broeke 2001; Fastenbauer 2007). These navigation reaches are often telecontrolled according to supervision architectures. The main control objective is to insure the seaworthiness requirements for the accommodation of the broad gauge boats. In particular, the

water level of the navigation channels has to be close to a Normal Navigation Level (NNL). The control of the water level is strongly constrained by the increasing of the gauge of the boats, the navigation schedules but also by extreme events due to global change. It is now accepted that climate change can cause longer periods of drought and stronger and more frequent flood events.

The effect of global change has been largely studied since several years starting from meteorological models at the planetary-scale. Based on climatic scenarios, predictive models of the water resources which will be available in future horizon from 10 years to 100 years have been proposed in the literature. They are based on social, economic and environmental aspects (Davies 2011; Graveline 2012; Murray 2012). In order to consider smaller scales, downscaling methods are proposed in the literature. In (Boe 2009; Ducharme 2010), the hydrological cycle of the main French river basins in the global change context has been studied. In (Garcia 2011), J. M. Garcia-Ruiz *et al.* focalize the study on the Mediterranean basin. To highlight the issues for the navigation sector of the climate change,

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the PIANC¹ organisation published in 2008 a report by considering various projected scenarios (EnviCom 2008). Future change projections suggest a global mean sea level rise of a few decimetres, a greater frequency and intensity of extreme weather events, a water temperature increase and a modification of the river morphology. The constraints linked to water supply and quality in inland navigation channels might be stronger and stronger. These conclusions are shared by other studies of the impact of climate change in U.K. (Iwac 2009; Arkell 2006) and China (Wang 2007). These studies are very instructive in relation to anticipating risks of climate change to the navigation. Some measures are also proposed for adapting the management of inland navigation networks in global change context. For waterway operation, it is recommended to implement new ICT on the networks, to improve the management of water flow with better forecasting methods of extreme events, to propose decision support systems which gather adaptive management strategies.

A structured framework is necessary to design new adaptive management strategies of inland navigation networks and to estimate its consequences on the water resource management. In (Duviella 2011), a supervision and hybrid control accommodation framework for reactive control of hydrographical networks composed of dams and interconnected rivers and channels, is proposed. It deals with a efficient water asset management via generic resource allocation. Although the proposed approach is based on supervision method and adaptive control strategies, it does not directly address the impacts due to climate change. Another interesting scheme to design adaptive management of water resources in a global change context is proposed in (Pouget 2012). A modeling tool called Water Change Modelling System (WCMS) is designed to integrate various models of the water cycle, such as hydrological, water management and water quality models. WCMS allows the creation of scenarios of extreme events according to a DPSIR framework (Driving Forces-Pressures-State-Impacts-Responses). However, this tool seems not being adapted to take into account the specificities of the management of inland navigation networks.

Thus, an adaptive and predictive control architecture is proposed in this paper to deal with the efficient management of these networks in a global change context. To achieve this aim, three challenges have to be considered. The first one consists in proposing an accurate modeling approach of navigation reaches. The second is to increase the knowledge about extreme events according to studies proposed in the literature. This knowledge is necessary to design realistic scenarios of extreme events. The third one is the pooling of the two first contributions. The proposed architecture is illustrated in the framework of a real system: the Cuiuchy-Fontinettes reach (CFR) located in the North of France. The structure of the paper is the following: Section II is dedicated to the description of the Cuiuchy-Fontinettes reach and to the management constraints of this system in a global change context. In Section III, the proposed architecture is presented. The modeling approach for inland navigation reach which is proposed in section IV. Section V is dedicated to the modeling step of extreme events, consequences of the climate change. In section VI, a simulation of a flood close to the CFR, and the functioning of the proposed architecture are shown. Finally, the summary and perspectives of this paper are given in section VII.

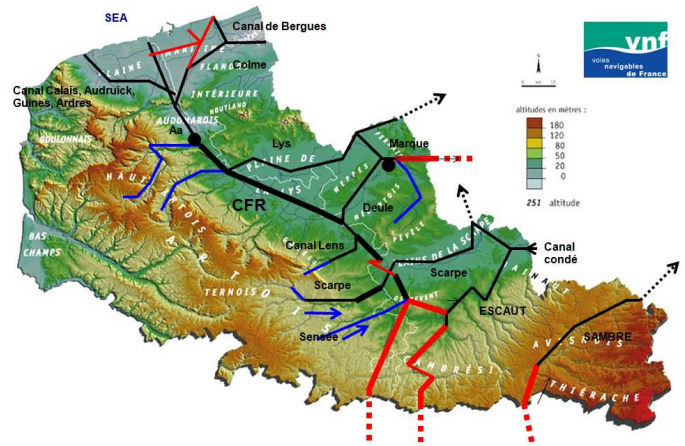


Fig. 1. Inland navigation network of the North of France.

2. CUICHY-FONTINETTES REACH

2.1 Presentation

The inland navigation network in the North of France is a large scale system composed of interconnected rivers and channels (see Figure 1). This network is equipped with control gates and locks which are dedicated to the navigation task. Some channels are completely artificial and have a transverse position relative to the watershed. It is the case of the CFR. The CFR is located between the upstream lock of Cuiuchy at the East of the town Bethune and the downstream lock of Fontinettes at the Southwest of the town Saint-Omer. The CFR is essential for navigation of broad gauge ships in the North of France. In effect, the Fontinettes lock allows to negotiate a topological obstacle with a compensation of a waterfall of 13 m between the Lys and Aa watersheds. Also, due to the CFR localization at the cross of three of the principal catchment areas of the region, its management impacts directly the water resource availability for users, industrials etc.

The CFR is managed by VNF (Voies Navigables de France) whose role is to maintain its relative level at $NNL = 4.26$ m (Normal Navigation Level) for the navigation accommodation. To reach this aim, three points of the CFR must be controlled: the first is the Cuiuchy lock and gate, the second is the Fontinettes lock and the third is the gate called "Porte de Garde". The length of the CFR is 42.3 km with a width equal to 52 m in average and no significant slope. The height of the lock at Fontinettes is 13 m whereas the lock at Cuiuchy is only 2 m. Considering the navigation flow, the water runs off from Cuiuchy to Fontinettes. The control of Cuiuchy and Fontinettes locks is principally constrained by the navigation demand. Each lock operation at Fontinettes leads to a consumption of water volume close to 25,000 m³. Moreover, a large number of intakes with anthropogenic origins (more than 320) supplies the CFR and often disturbs the control of water level.

2.2 Management rules

The management rules of inland navigation reach, especially for the CFR, consists in maintaining the NNL. this level is controlled with gates that supply water to the reach and compensate the effect of the locks that are operated following the navigation requirements. The level of each reach is controlled

¹ Permanent International Association of Navigation Congresses

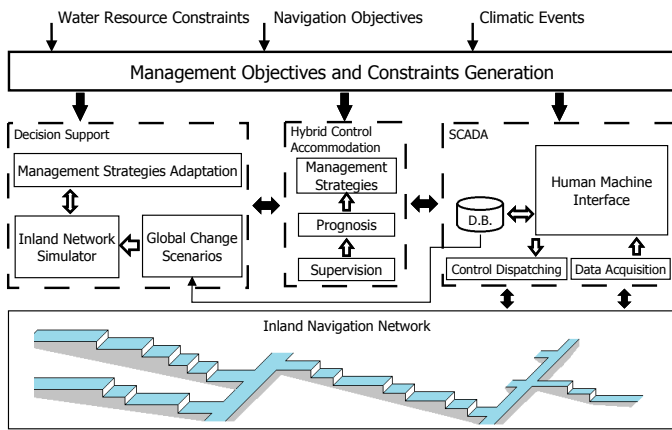


Fig. 2. Adaptive and predictive control architecture.

according to the level of upstream reach and several affluents when it is possible.

During drought periods, the priority given to the water use for navigation is the lowest compared to those for drinking water, for industry, for agriculture and for ecological aims. In effect, during these periods the water temperature can increase. The consequences are a modification of the ecosystem and a decrease of the oxygene in the water. It is necessary to circulate the water and thus operate the gates and locks. This leads to the decrease of the available volume of water. Under these strong constraints, it is necessary to accommodate the navigation. Thus, convoys of ships have to be planned.

During wet periods, the navigation channels are used to stock the maximum volume of water to avoid floods in the watersheds. For forecasted floods, the level of the channels are lowered by several centimeters, hours before their occurrence. However, each navigation reach has a maximum limit. For the CFR this limit is 0.5 m up above the NNL. Beyond these maximum levels, a protocol submitted to prefectural decision is implemented to determine the area that will be impacted by the floods. In addition, even if this is not the case of the CFR, erosion phenomena might damage the navigation channels.

In a global change context, the drought and wet periods with occurrence of floods will be increased. Thus, it is necessary to adapt the current management strategies of the inland navigation networks. To achieve these aims an adaptive and predictive control architecture is presented in the next section.

3. ADAPTIVE AND PREDICTIVE CONTROL ARCHITECTURE

An adaptive and predictive control architecture is proposed to improve the management of inland navigation networks against global change impacts (see Figure 2). This architecture is based on a SCADA (Supervisory Control And Data Acquisition) system which allows the tele-management of the network. Set-points defined by the manager of the system or by the management strategies are sent to the actuators. The data measured on the network are saved in a data-base after a reconciliation step. This step is necessary to eliminate wrong data, and to detect faults on sensors or actuators. A Human Machine Interface (HMI) allows the supervision of the inland navigation network.

The control of the system is carried out according to the Management Objectives and Constraints Generation module (MOCG). This module regroupes all the management protocols. These ones take into account the navigation objectives, the constraints of the water resource uses and the climatic events.

The Hybrid Control Accommodation module (HCA) is composed of three blocks. The Supervision block consists in determining the current state of the system according to the measured data. The predictive characteristic of the architecture is included in the Prognosis block. It consists in forecasting the flood events and the drought periods, *i.e.* the future state of the system, according to predictive modeling approaches. Finally, the Management Strategies block defines the setpoints which have to be sent to the actuators of the system. Theses strategies can be adapted according to the Decision Support module (DS).

The DS module is designed to define adaptive management strategies of inland navigation networks, and to test the resilience of the inland navigation reaches. The resilience is defined as the capacity of the reach to resist to an extreme event. This module communicates with the MOCG and the HCA modules, and the SCADA via the HMI. The past events can take into account thanks to the data base. The DSM is based on three blocks. The Management Strategies Adaptation block (MSA) is used to design adaptive management strategies of inland navigation systems according to constraints and management objectives from the MOCG module and the current and forecasted states of the system. The Global Change Scenario block (GCS) aims at defining realistic scenarios of extreme events according to knowledge about the consequences of the global change, to past events and to predictive modeling approaches. Finally, the Inland Navigation Simulator block (INS) is used to simulate the dynamics of inland navigation networks. This block is linked with the GCS and SM blocks in order to simulate extreme events and to test management strategies, respectively. A recursive step is proposed to test and to adapt the management strategies. Then, the results of the DS module, in particular the adaptive management strategies, can be applied on the real system via the HCA module. The design of the DS module requires the proposition of a model of the inland navigation reaches and a modeling step of extreme events.

4. INLAND NAVIGATION REACH MODELING

An inland navigation reach is an open-channel system characterized by large dimensions and nonlinear dynamics with varying delays. They have generally no significant slope and can be subjected to wave phenomena which are caused by operations of the locks (Blesa 2012; Clemmens 2012; Duviella 2013). According to the dimension of the locks, the amplitude of the wave can exceed several centimeters. The software SIC (Malaterre 2006) is used to model the dynamics of inland navigation reaches. This software can be easily coupled with Matlab/Simulink. The main advantage is that structure offers the possibility to develop models of the dynamics of locks or gates in Simulink, such as models of undershot gate and overshot gate (Euren 2007), or hybrid model of undershot/overshot gate (Le Porcher 2012).

The operation of a lock leads to a gain or a loss of a volume V during a time T . This corresponds to a maximum discharge which goes in the reach or out the reach. It is modeled with a trapezoidal profile. For example, the operating of the Cuinchy

lock corresponds to a volume of 3700 m^3 during 6 minutes with a trapezoidal profile, and a maximum discharge equal to $10.8 \text{ m}^3/\text{s}$. The operating of the Fontinettes lock corresponds to a volume of 25000 m^3 during 15 minutes with a trapezoidal profile, and a maximum discharge equal to $29 \text{ m}^3/\text{s}$.

5. MODELING STEP OF EXTREME EVENTS

5.1 Characteristics of extreme events

The modeling step of extreme events is divided in two parts. The first one consists in considering the drought periods, the second one the flood events. Even if both of these events impact the navigation task, they can not be modeled with the same approach.

While considering drought periods, scenarios due to global change consist in an elevation of the temperature and a decrease of available water resources. The time-scale of these events is generally large, *i.e.* from several days to several months. The space-scale is also large. To model drought events, it is possible to use the results of studies which are available in the literature, such as (Boe 2009; Ducharne 2010). These results have to be transposed to the North of France in order to define scenarios of drought. These scenarios could be sharpened by considering past drought events. In effect, a data base of more than 10 years is available.

The flood events are generally more localized and on smaller time-scales. The modeling of these events requires a good knowledge of the watershed dynamics and flood forecasting techniques. This knowledge is based on experience gathered from past floods occurred on several rivers (Pitt 2007), or historical studies (Sheffer 2008). In addition, several forecasting flood methods have been proposed in the literature. Some of them are based on rainfall/runoff models which involve a precise knowledge of the physico-geometric characteristics of the catchment areas (Calvo 2009; Laurain 2010). Others approaches based on stochastic models (Clove 2009; Ramos 2012; Wetterhall 2013), artificial intelligence approaches (Talei 2010), or black-box model (Duviella 2012) can be used when the amount of data collected from the catchment area is sufficiently large and rich (over several years or decades period). The modeling of flood events is highlighted in the next subsection.

5.2 Modeling step of flood events

The modeling approach of flood events which are used in this paper was defined in (Duviella 2012). It is summarized herein. Its main advantage is that no prior knowledge about the characteristics of the watershed is necessary, but only a set of large enough historical data of the system. The rainfall/runoff relation is modeling according to a nonlinear black-box model. It is assumed that the rainfall and the water level in the river can be related by a model of the form:

$$y(k) = \theta^\top \vartheta(\varphi_H(k)), \quad (1)$$

where θ is a vector of parameters and $\varphi(k)$ is the regressor vector defined as

$$\varphi_H(k) = [y(k-H-1) \dots y(k-H-n_a) \\ u(k) \ u(k-1) \dots u(k-H-n_b)]^\top, \quad (2)$$

where y is the water level at one point of the river, u is the rainfall, n_a and n_b are the orders of the model. The integer H is the predictive horizon. ϑ is a nonlinear map from the space of the regressors \mathbb{R}^d , $d = n_a + n_b + H + 1$, to \mathbb{R}^{M+1} defined by:

$$\vartheta(\varphi) = [1 \ k(c_1, \varphi) \dots k(c_M, \varphi)]^\top.$$

Here, the functions $k(c_i, \cdot)$, $i = 1, \dots, M$, refer to a gaussian RBF (Radial Basis Function) defined on \mathbb{R}^d by:

$$k(c_i, \varphi) = \exp\left(-\frac{\|c_i - \varphi_H\|_2^2}{2\sigma^2}\right)$$

with c_i , $i = 1, \dots, M$, denoting the so-called centers of the RBF and $\sigma^2 > 0$ its width. The vector $\theta = [\theta_0 \ \theta_1 \dots \theta_M]^\top$ is the parameter vector to be estimated.

The parameter vector θ is determined by minimizing the cost functional

$$\mathcal{J}(\theta) = \sum_{k=1}^N (y(k) - \theta^\top \vartheta(\varphi(k)))^2 + \gamma \|\theta\|_1 \quad (3)$$

where $\|\theta\|_1 = |\theta_0| + \dots + |\theta_M|$ is the ℓ_1 -norm of θ , and γ is a regularisation parameter. The optimization algorithm which leads to the determination of θ is given in (Duviella 2012). The objectif is to predict at time k the level of water in the next f hours. Thus, it is necessary to compute $\hat{y}(k+f|k)$ based on the past inputs and outputs and the forecasted inputs (rainfall) $u(k), u(k+1), \dots, u(k+f)$, where f is the prediction horizon.

In this paper, the prediction of rainfall over 24 hours is considered available. In other case, uncertainties in the proposed modeling approach have to be taken into account to consider the stochastic properties of climate events. Anyway, the recursive property of the proposed algorithm seems robust against uncertainties because the model parameters are updated in continuous way.

6. ADAPTIVE AND PREDICTIVE CONTROL OF THE CUINCHY-FONTINETTES REACH

To show the functioning of the proposed architecture, a flood event scenario is built by considering the CFR. The simulation consists of one week of navigation with crossing of ships from Cuinchy and from Fontinettes, and of the occurrence of the flood on a river which can supply the CFR thanks to the gate called *Porte de Garde*. The CFR is modeled with SIC (*see* Figure 3). The Cuinchy gate is a spillway. The *Porte de Garde* gate is located at 28.7 km from the Cuinchy lock. It is an undershot/overshot gate with an operating range of $Q_L = \pm 7 \text{ m}^3/\text{s}$. The dynamics of these actuators is modeled according to approaches which are proposed in the literature (*see* section 4) and implemented using Simulink. The dynamics of the Cuinchy and Fontinettes locks during operation is given in section 4.

The flood is built according to real data of rainfall and measured level, of one typical period of the year; autumn (*see* Figure 4). The measured level is depicted in blue continuous line, and the predicted level in magenta dashed line. Levels are forecasted on a future horizon of 24 hours according to the proposed nonlinear black-box model. The parameters are tuned as $n_a = 10$, $n_b = 10$, $\sigma = 4$, $\gamma = 0.05$ and $M = 30$. The forgetting factor is tuned as $\lambda = 0.999$.

The main objective is to accommodate navigation with a CFR level in the operating range $\text{NNL} \pm 0.3 \text{ m}$. In normal situation,

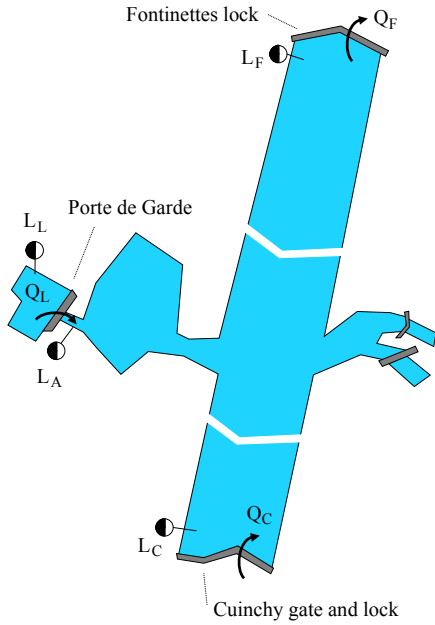


Fig. 3. Scheme of the Cuinchy-Fontinettes navigation reach.

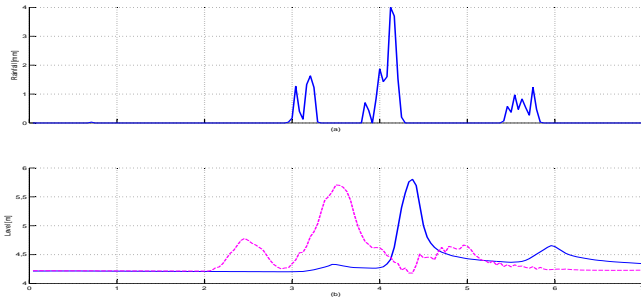


Fig. 4. (a) Rainfall and (b) the real (blue continuous) and predicted (magenta dashed) water levels of the flood scenario.

to respect this condition, the discharge in Cuinchy Q_C is equal to $2.4 \text{ m}^3/\text{s}$. The picks in Figure 5.b and 5.d correspond to the lock operations in Cuinchy and in Fontinettes, respectively. The flood occurs during the fourth day and it is forecasted 24 hours before (see Figure 5.a). As soon as the pick of flood is predicted, the discharge Q_C is tune to 0, excepted of the lock operations. During the occurrence of a flood, the maximum volume of water is stocked in the CFR with a maximum discharge $Q_L = 7 \text{ m}^3/\text{s}$ (see Figure 5.c). This maximum is reached during the occurrence of the flood. Finally, the adaptive and predictive control of the CFR leads to limitation of the impact of the flood in the Lys river by a storage of maximum water volume in the CFR and allows the navigation. In fact, the levels of the CFR (see Figure 5.e) are kept in the navigation operating range.

7. CONCLUSION

The fundamentals of an adaptative and predictive control architecture is proposed in this paper. This architecture is defined to improve the management of inland navigation networks in a global change context. It is based on a Hybrid Control Accommodation and Decision Support modules, and on also a SCADA system. An inland modeling method and a flood event forecasting approach are proposed to achieve the aims of these module. The proposed architecture is dedicated to the manage-

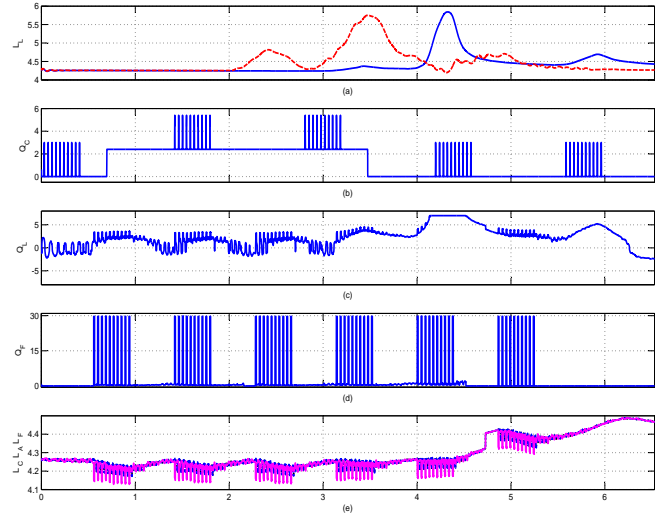


Fig. 5. (a) real (blue continuous) and predicted (red dashed) levels of Lys river, (b) Cuinchy discharge, (c) Lys discharge, (d) Fontinettes discharge and (e) Cuinchy (dashed line), Aire (dotted line) and Fontinettes (continuous line) levels of scenario 2.

ment of a real inland navigation reach. Its efficiency is shown by simulation by considering a scenario of flood. In future works, it will be necessary to improve the modeling approaches of the inland navigation networks and of the extreme events. The SCADA architecture must also be developed according to existing tools.

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