

AUTOMATIC CONTROL TO IMPROVE THE SEAWORTHINESS CONDITIONS IN INLAND NAVIGATION NETWORKS

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ABSTRACT

This paper focuses on the Normal Navigation Level (NNL) control of a hydraulic channel that is located in the northwest of France and belongs to the Europe Inland Navigation Network. This system is a large scale system with several inputs and outputs that nowadays is operated manually by the lockkeepers with the aid of local controllers that try to maintain the level of the channel as close as possible to the NNL in order to fulfil the seaworthiness requirements. Last years, the channel has been equipped with electronic sensors in order to have better knowledge of its behaviour, provide online its state to the lockkeepers and improve its management. In this work, an automatic control based on a Model Predictive Controller (MPC) is proposed. The MPC controller is based on a model of the system and, with the available data, provides automatically the suitable control inputs (flows) in order to maintain the level the channel despite the locks operation that produces wave phenomena and other unknown inputs along the channel. A numerical simulator of the system based on the Saint-Venant Equations and calibrated with real data has been developed in order to verify the effectiveness of the proposed automatic controller.

KEYWORDS

Inland Navigation Networks, Seaworthiness, Automatic Control, Locks Operation.

INTRODUCTION

The use of Inland Navigation Networks as an alternative to land transport provides economic and environmental benefits (Mihic et al 2011, Mallidis et al 2012). Europe's network of navigable rivers and canals offers access to the continent's urban and industrial centres, allowing for the more efficient, quieter, and safer transport of goods (Brand et al 2012). In this context, navigation channel networks in the north of Europe will have to be able to accommodate large broad gauge boats in few years. Operation researches (Dekker et al. 2011), or simulation tools (Almaz and Altiok 2012), based on Information and Communication Technology (ICT), are proposed in the literature in order to improve the inland navigation. In addition, managers have to improve the seaworthiness requirements of their navigation channels, in particular on the water level which has to be closer to the Normal Navigation Level (NNL) than until present. These strong constraints impose the development and tuning of new control algorithms.

On the other hand, in the last years the use of Information and Communication Technology has dramatically been increased. This increased use allows supporting traffic management in inland navigation and providing inland shipping with a competitive edge over road transport. This information can be used for automatic control purposes that provide more accuracy and reliability than manual control.

By focalizing on the navigation networks of the north of France, in particular on the Cuiuchy-Fontinettes Reach (CFR), this paper presents the specific characteristics of this system and the control problems inherent in its operation, particularly the phenomena of waves. The CFR is a MIMO (Multi Input-Multi Output) non-linear dynamic system with variable delays that is equipped with gates, locks and sensors.

The phenomena of waves occur when the locks are operated. They cause waves of more than 10 cm along the channel which interferes with navigation. Thus, one of the management objectives of the CFR consists in reducing the amplitude of the wave by means of automatic control techniques.

Firstly, the simulation model of the considered reach, which is based on the Saint-Venant equations, is proposed and calibrated using real measured data. Then, a control algorithm is proposed in order to compensate or to reduce the waves. The control algorithm is tuned and evaluated by considering scenarios of locks operation in simulation using the developed numerical simulator. The preliminary results show the effectiveness of the proposed control technique and the interest in improving it to satisfy the seaworthiness requirements.

DESCRIPTION OF THE SYSTEM

In the north-west of Europe, a large network of inland waterways is located and used to accommodate large broad gauge boats (*see* Figure 1). The part of this network located in France is managed by the French public institution VNF (Voies Navigables de France) whose role is to operate and develop this network, in order to improve the efficiency of the navigation and resource water management. The inland waterways which are managed by VNF consist of 6,200 km of canals and rivers.

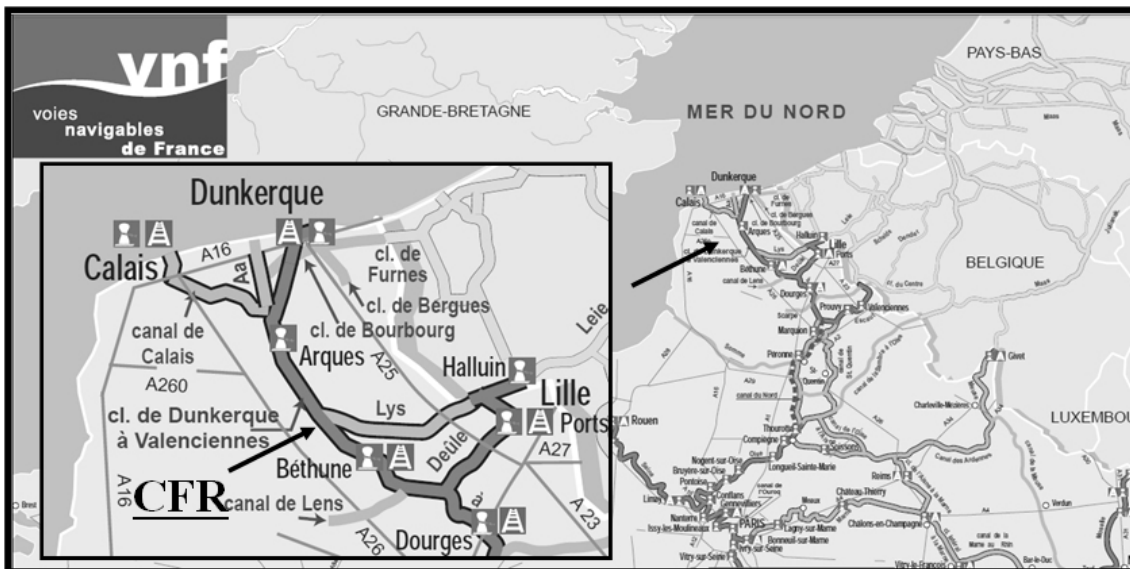


Figure 1: The inland waterways network located in the north-west of Europe.

By focalizing on this network, in particular in the north region of France, VNF Nord Pas-de-Calais manages more than one hundred of navigation locks, and can control the dispatching of water volume between nearly ten catchment areas. One of these navigation channels, the Cunchy-Fontinettes Reach (CFR), has a crucial importance due to its localization, *i.e.* between two major catchment areas of this region, and its

size, *i.e.* more than 40 km long. The main use of the CFR is for navigation purposes. However, it can be used to stock water volumes during wet periods in order to avoid or to limit floods on the two catchment areas, and during dry period to supply water to these two catchment areas.

The CFR is located between the upstream lock of Cuinchy at the East of the town Bethune and, at the Southwest of the town Saint-Omer, the downstream lock of Fontinettes (*see* Figure 2). The first part of the channel, *i.e.* 28.7 km from Cuinchy to Aire-sur-la-Lys, is called “canal d’Aire” and was built in 1820. The second part of the channel, *i.e.* 13.6 km from Aire-sur-la-Lys to Saint-Omer, is called “canal de Neuffossé” and was built in the eleventh century. The channel is entirely artificial and has no significant slope. Considering the navigation flow, the water runs off from Cuinchy to Fontinettes.

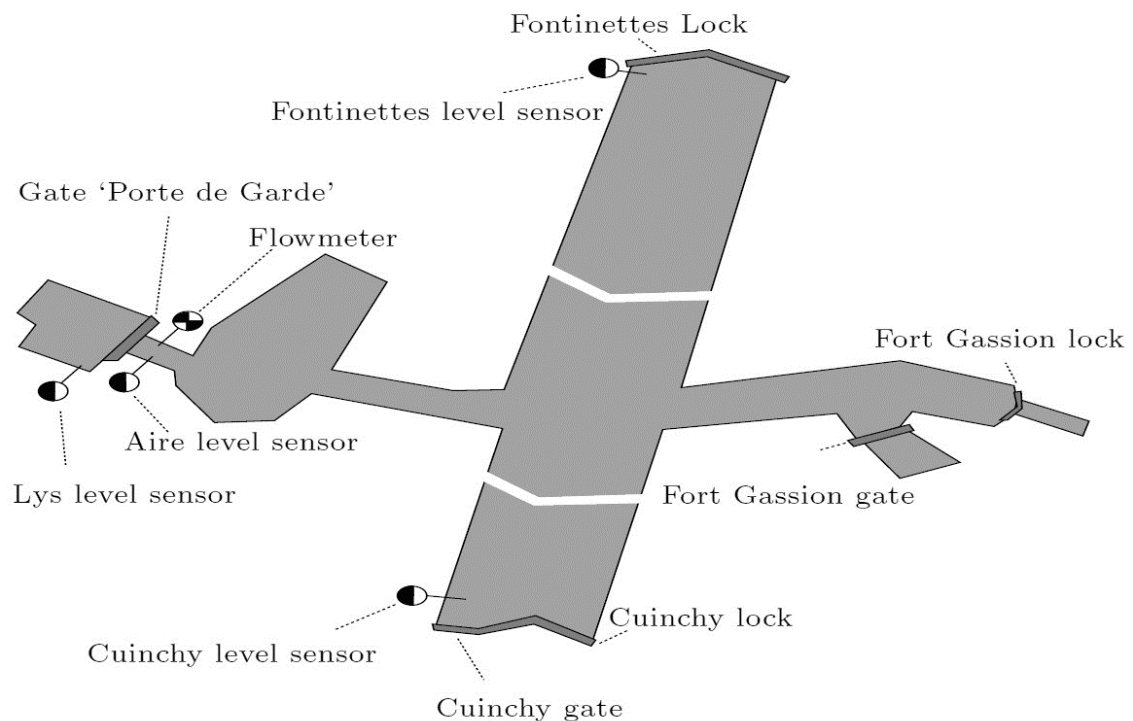


Figure 2: Scheme of the Cuinchy-Fontinettes navigation channel.

By considering navigation constraints, the water level of the CFR has to be maintained at the $NNL = 19.52 \text{ m}$ ($NNL = \text{Normal Navigation Level}$). An operating range around the NNL is defined by the Highest Navigation Level (HNL) and the Lowest Navigation Level (LNL). If the water level of the CFR is lower than the LNL or higher than the HNL , the navigation is stopped. The water level of the CFR has to be maintained in the operating range [LNL, HNL], despite perturbations and exceptional situations (drought or flood). These perturbations are due to more than 300 unknown inputs along the reach and the locks operations. The main perturbation is Fontinettes lock operation which produces a wave whose amplitude is more than 10 cm and travels at a speed of about 20 km/h along the channel which interferes with navigation. When the wave arrives to Cuinchy, it rebounds and come back with an amplitude of 8 cm . The wave remains in the channel with successive rebounds until steady state, approximately 15 hours, decreasing 1 cm the level of the channel. A Fontinettes lock operation is equivalent of a withdrawal of $25,000 \text{ m}^3$ in 15 minutes. The Fort Gassion gate and lock, presented in figure 2, are two of the unknown inputs and are operated for sporting purposes.



Figure 3: A ship inside the downstream lock (Fontinettes) during the filling process.

To reach the aim of maintaining the NNL, VNF has equipped the channel with limnimeters (in Cuinchy, Aire and Fontinettes) and controls the flow discharges in input and output of the CFR at these three points: the first is the Cuinchy lock and gate, the second is the Fontinettes lock and the third is the gate called “Porte de Garde” at Aire-sur-la-Lys. The control of Cuinchy and Fontinettes locks is constrained by the navigation demand. The “Porte de Garde” gate at “Aire-sur-la-Lys” and the Cuinchy gate are used to control the water level in the CFR, without being constrained by the navigation demand. The “Porte de Garde” gate allows exchanges between the CFR and the Lys River, and authorizes the water runoff in both directions, *i.e.* from the CFR to

the Lys River, or from the Lys River to the CFR. On the other hand, the Cuinchy gate allows provide extra water to the channel.

Nowadays the operating range of the system, defined by LNL and HNL, is 19.52 ± 0.25 m (level respect to the mean sea level) during the navigation schedule time: 8:00 am-8:00 pm. In the future, in order to accommodate larger vessels, this range will be reduced to 19.52 ± 0.15 m and the navigation schedule time will be expanded to the 24 hours of the day.

Control strategies of the gates and locks in Cuinchy, Aire and Fontinettes have to be designed to limit, particularly, the impact of the operation of the Fontinettes lock. Firstly, it consists in understanding and in modelling the dynamics of the CFR. Then, the designed control strategies have to be tuned, tested and validated by simulation before to be implemented in the real system.

MODELLING OF THE CUINCHY-FONTINETTES REACH

The CFR is 42.3 km long, with no significant slope. Although it is artificial, the CFR is composed of more than 400 different cross sections, with depth going from 0.3 m for the banks, to 4.79 m, and a depth average, h , around 4.2 m. As a first modelling approach, a mean profile of the CFR is considered (*see* Figure 4), with the following geometrical characteristics:

- B , the bottom width of 34 m,
- Z , the height of 4.7 m,
- f , the average fruit of the banks of 1.73 m,

- h , the average level depth of 4.2 m
- NNL , the Normal Navigation Level and its Higher and Lower bounds

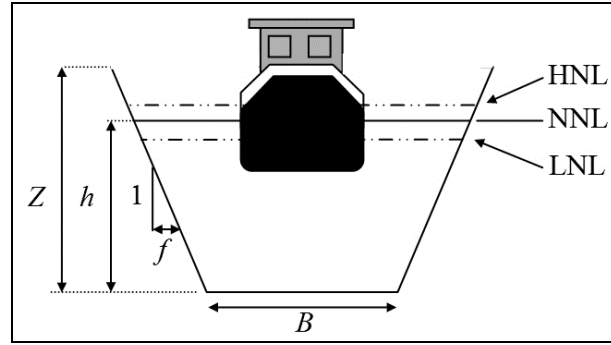


Figure 4: Average geometrical characteristics of the CFR.

In this work, the real canal behaviour has been accurately modelled by Saint-Venant's equations (Chow, 1959) and reproduced using a high-fidelity simulator and implemented in the software Matlab-Simulink[®]. This simulator solves numerically the Saint-Venant's equations as usually done in existent commercial open-flow canal simulators (Malaterre, 2006) after been calibrated with real data.

The Saint-Venant equations are partial-differential equations that describe accurately the dynamics in a one-dimensional free surface flow. These equations express the conservation of mass and momentum principles in a one-dimensional free surface flow:

$$\frac{\partial Q}{\partial x} + \frac{\partial S}{\partial t} = 0$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^2}{S} \right) + gS \frac{\partial h}{\partial x} - gS(I - J) = 0 \quad (1)$$

where $Q = Q(x,t)$ is the flow (in m^3/s), $S = S(x,t)$ is the cross-sectional area (in m^2), t is the time variable (in s), x is the spatial variable (in m), measured in the direction of the movement, h is the spatial variable corresponding of water elevation (in m), g is the gravity (in m/s^2), I is the bottom slope and J is the friction slope.

After the simulator has been implemented, different discharge schedules have been simulated in order to evaluate the influence of the time in the filling/emptying lock procedure and the level evolution. The results of these simulations are shown in Figures 5 and 6.

Nowadays the time in the filling of the Fontinettes lock is 15 minutes and the amplitude of the wave is approximately 12 cm. If the filling of the lock is carried out slower than it is currently done, this amplitude can be reduced as it shown in Figure 5.

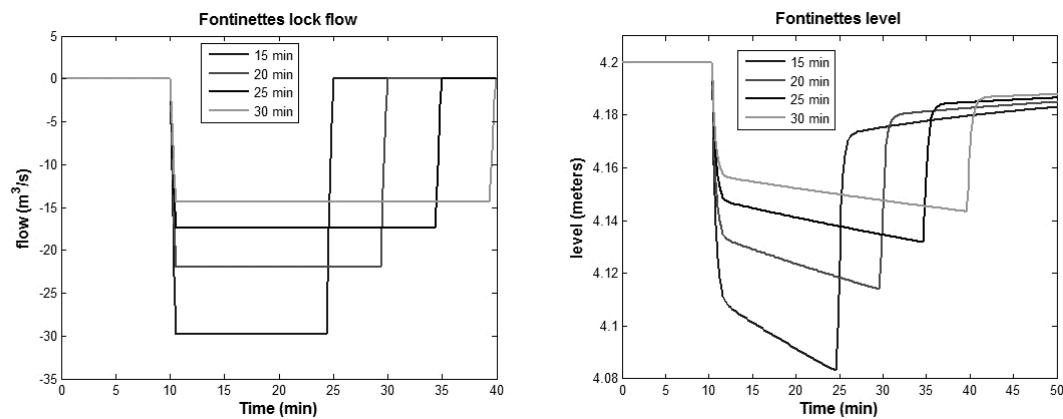


Figure 5: Fontinettes lock flow and level evolution for different discharge schedules

On the other hand, the operation of the Cuiuchy lock is much less critical. In the current operation, the time in emptying of the Cuiuchy lock is 5 minutes and the amplitude of the

wave is approximately 4 cm. If the filling of the lock is carried out slower than it is done now, this amplitude can be reduced as it shown in Figure 6.

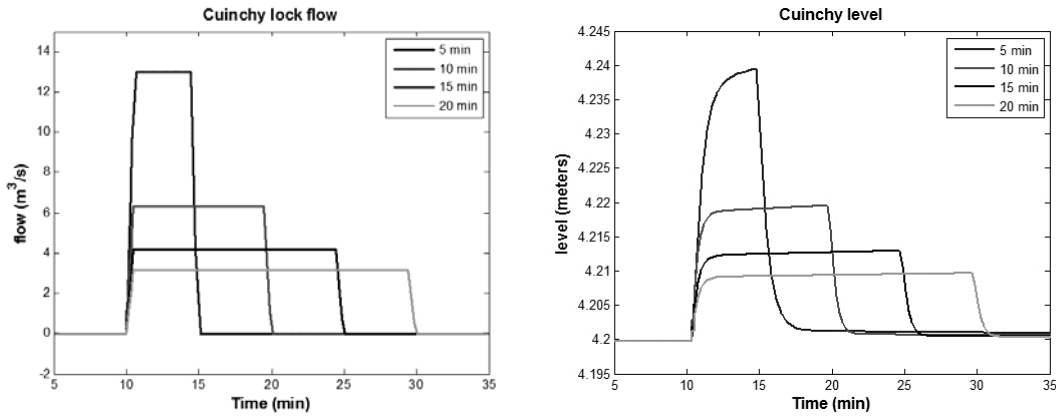


Figure 6: Cuinchy lock flow and level evolution for different discharge schedules

DESIGN OF A CONTROL STRATEGY

The complex dynamics of the system is basically due to the existence of multiple inputs/outputs and the large delay between them, makes the Model Predictive Control (MPC) a suitable candidate to perform the automatic control algorithm. The Model Predictive Control (MPC) is an advanced method of process control that considers intrinsically these complex behaviours (Camacho and Bordons, 2004) (Maciejowski, 2002). The idea behind MPC is to start with a model of the open-loop process that explains the dynamical relations among system's variables (command inputs, internal states, and measured outputs). Then, constraint specifications on system variables are added, such as input limitations (typically due to actuator saturation) and desired ranges where states and outputs should remain. Desired performance specifications complete the picture and are expressed through different weights on tracking errors and actuator efforts (as in classical linear quadratic regulation). The rest of the MPC design is automatic. First, an optimal control problem based on the given model, constraints, and

weights, is constructed and translated into an equivalent optimization problem, which depends on the initial state and reference signals. Then, at each sampling time, the optimization problem is solved by taking the current (measured or estimated) state as the initial state of the optimal control problem. For this reason the approach is said predictive, as in fact the optimal control problem covers the time interval that starts at the current time up to a certain time in the future. The result of the optimization is an optimal sequence of future control moves. Only the first sample of such a sequence is actually applied to the process, the remaining moves are discarded. At the next time step, a new optimal control problem based on new measurements is solved over a shifted prediction horizon. For this reason the approach is also called “receding horizon” or “rolling-horizon” control. Note that the receding horizon mechanism represents a way of transforming an open-loop design methodology (namely, optimal control) into a feedback one, as at every time step the input applied to the process depends on the most recent measurements.

In Figure 7, the scheme of the MPC used for control the CFR system is presented. The inputs of the system are: u_1 and u_2 (in m^3/s) that corresponds to the Cuinchy and Lys gate flows, respectively. The outputs of the system are: y_1 , y_2 and y_3 (in m) that are the Cuinchy, Lys and Fontinettes levels, respectively. Finally, the disturbances are the Fontinettes and Cuinchy locks operations and other unknown inputs along the channel.

The constraints of the inputs are:

$$\begin{aligned} 0 &\leq u_1 \leq 10 \\ -7 &\leq u_2 \leq 7 \end{aligned} \tag{2}$$

And the control objective is to maintain the level outputs inside the seaworthiness conditions

$$LNL \leq y_i \leq HNL, \quad \forall i = 1,2,3 \quad (3)$$

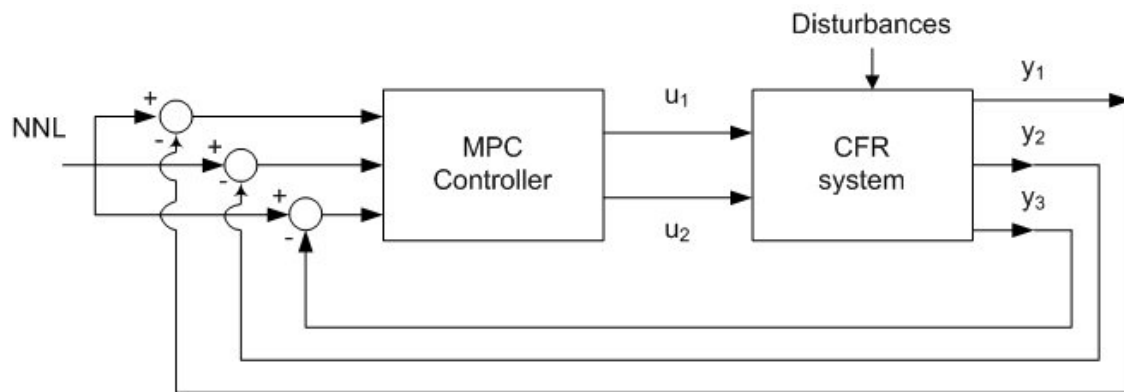


Figure 7: Automatic control scheme

The objective of the MPC is to keep, as much as possible, the outputs of the system (measured levels in the reach) close to the Normal Navigation Level despite the perturbations of the system by introducing the suitable inputs (flows) computed by the MPC and considering constraints (2). In case of flood and dry scenarios, constraints can be modified and MPC controlled reconfigured.

MPC algorithms need a discrete-time model of the plant in order to compute estimations of the outputs for future time steps as:

$$\begin{pmatrix} y_1(k) \\ y_2(k) \\ y_3(k) \end{pmatrix} = \begin{pmatrix} G_{11}(q^{-1}) & G_{12}(q^{-1}) \\ G_{21}(q^{-1}) & G_{22}(q^{-1}) \\ G_{31}(q^{-1}) & G_{32}(q^{-1}) \end{pmatrix} \begin{pmatrix} u_1(k) \\ u_2(k) \end{pmatrix} \quad (4)$$

Saint Venant equations (1) for an arbitrary geometry lack of analytical solution are not useful for obtain the discrete time model (4).

G_{11} , G_{12} , G_{21} , G_{22} , G_{31} and G_{32} have been identified applying superposition and conventional identification techniques (Ljung, 1987) with a sampling time of $T_s = 5 \text{ min}$. First, a sequence of flow, rich enough under the identification point of view, has been applied in Cuinchy gate (u_1) then least squares identification methods have been applied to outputs y_1 , y_2 and y_3 obtaining G_{11} , G_{21} and G_{31} . The same process has been repeated in Lys gate (u_2) to obtain G_{12} , G_{22} and G_{32} .

Once the mathematical model has been obtained, the controller has been applied to real scenarios (based on real data available) reproduced using the Saint-Venant Simulator. In these simulations, it has verified that the MPC controller is able to maintain the seaworthiness conditions (3) in the current operation mode: 8 am – 8pm navigation schedule with 10 operations in every lock. On the other hand, the different lock discharge schedules showed in Figures 5 and 6 have been applied and it has been verified that for slower lock operation it is easier to guarantee the seaworthiness conditions.

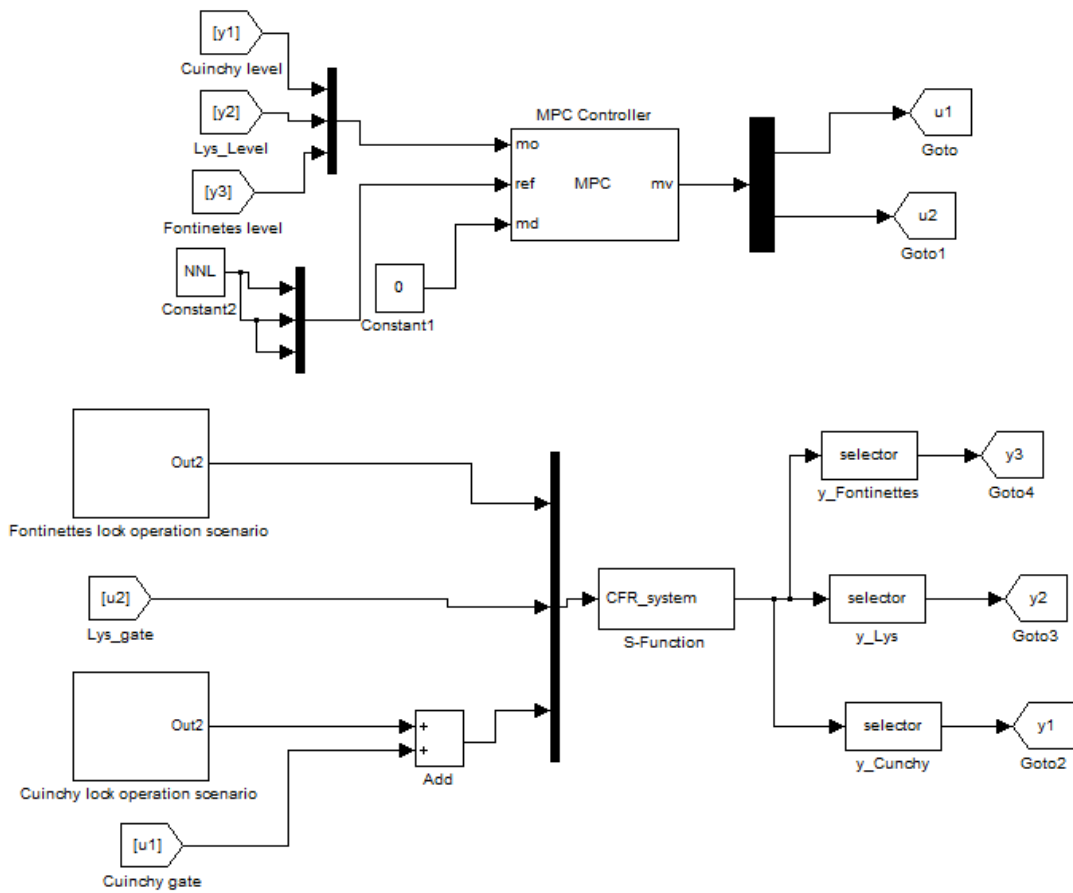


Figure 8: CFR simulator implemented in Matlab-Simulink©

Moreover, future hypothetical scenarios that consider 24 hours of navigation schedule with 20 operations in every lock have been simulated and it has verified that the proposed controller is able to guarantee the future seaworthiness conditions (3) with $LNL=NNL-0.15$ and $HNL=NNL+0.15$.

Figure 9 shows the evolution of the level in the three controlled points of the channel using the MPC controller and increasing the Fontinettes time lock operation 5 minutes. In this figure, the evolution of the gate flows (control inputs) computed by the MPC

controller and applied to the system are showed as well. It can be seen that the levels are always inside the bounds that define the seaworthiness.

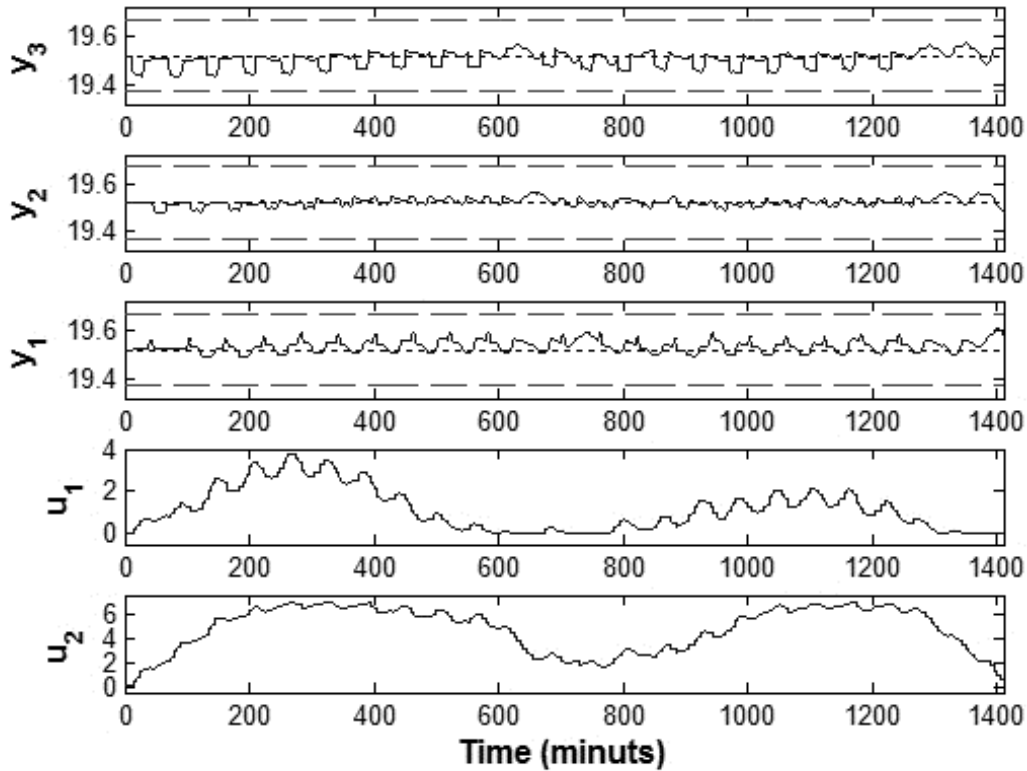


Figure 9: Evolution of Outputs (with seaworthiness bounds) in meters respect to the mean sea level and inputs in m^3/s in a 24 hours hypothetical scenario

CONCLUSIONS

In this paper, a MPC controller has been proposed for the control of the level in an inland navigation channel located in the north west of France. The automatic control provides better accuracy than human operation and allows guaranteeing stronger seaworthiness conditions. These stronger conditions are necessary to accommodate large broad gauge boats and expand the navigation schedule. And therefore, provide inland shipping with a competitive edge over road transport. Finally, the proposed

controller has been successfully validated in real and hypothetical scenarios using a high-fidelity simulator. The future purposes consist in deal with possible faults that can affect to sensors/actuators of the real system. Another issue will consist in considering the effect of the unknown inputs along the channel. These effects are very important in extreme episodes as flood and drought. Finally, after validation and simulation steps, an implementation on-line of the proposed technique on the real system may be considered at term.

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