Decentralized Fault-Tolerant Control of Inland Navigation Networks: a Challenge

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Abstract. Inland waterways are large-scale networks used principally for navigation. Even if the transport planning is an important issue, the water resource management is a crucial point. Indeed, navigation is not possible when there is too little or too much water inside the waterways. Hence, the water resource management of waterways has to be particularly efficient in a context of climate change and increase of water demand. This management has to be done by considering different time and space scales and still requires the development of new methodologies and tools in the topics of the Control and Informatics communities. This work addresses the problem of waterways management in terms of modeling, control, diagnosis and fault-tolerant control by focusing in the inland waterways of the north of France. A review of proposed tools and the ongoing research topics are provided in this paper.

1. Introduction

Inland navigation networks cover more than $38,000$ km in Europe and more than $8,500$ km in France. They are used to transport billions of tons of water per year with a demand increase that should reach $+35\%$ by 2050 in Europe [6]. Inland navigation takes part in the Trans-European network program (TEN-T[1]), which promotes the development of transport infrastructure policies to close the gaps between Member States' transport networks and to guarantee seamless transport chains for passengers and freight. As an example of this, the new Seine-Nord canal between the French towns of Compiègne and Creil will connect Paris to the Belgian and Dutch waterways. In the north of France, the Nord-Pas de Calais region is seeking to shift 20% of transport volume from road to rail and navigation by 2050[2]. An intensification in the use of inland waterways is expected in the near future, mainly due to the fact that navigation transport offers an environmental-friendly and economical alternative in comparison to road transport [9]. This increase of navigation demand will be in the context of climate change, since it is now recognized that inland waterways will be impacted by global change [2, 3, 16, 29, 64]. Thus, the constraints on inland waterway management, and more exactly on the available water resources dedicated to the navigation, will be more severe.

Inland waterways management is a synonym of water resources management, as it is necessary to allocate the water resources amongst the networks [12, 14, 43, 44] and to control the water levels

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[1] http://ec.europa.eu/transport/themes/infrastructure/ten-t-guidelines/index_en.htm
[2] https://www.nordpasdecalais.fr/upload/docs/application/pdf/2014-09/schema_climat-web-170914.pdf

everywhere. By focusing on the water level control, the main objectives can be efficiently reached by the design of modeling approaches, control techniques, fault detection and isolation (FDI) methods and finally fault-tolerant control (FTC) strategies. The modeling approaches are useful for the design of control, FDI and FTC methods, even if some model-free based control techniques are proposed in the literature for hydroelectric power plants [31], model-free based FDI for a gate of waterways [33] or a dam-gallery open channel system [1]. The control algorithms have to take into account the complexity and the scale of the inland waterways by considering centralized [61] or decentralized approaches [17, 46, 50, 51]. FDI techniques can be based on models of the systems [5, 30, 42], on the measured data [15] or on both [26]. Finally, FTC strategies aim at allowing the system to continue operating properly with fault occurrences [25, 67]. To the knowledge of the authors, the proposal of FTC strategies for inland waterways is an open issue. The development of these approaches is still an ongoing research topic if all the complexity of the waterway networks has to be taken into account.

After describing the characteristics of inland waterways and their management objectives in Section 2, the application of FTC to inland waterways is presented in Section 3 by proposing an architecture for interconnected systems. This architecture is based on active FTC strategy that aims at reconfiguring control actions so that the stability and an acceptable performance of the entire system can be maintained. The proposed scheme is built on modeling approaches that are described in Section 4. The decentralized control techniques are discussed in Section 5, and Section 6 presents the FDI methods. For each section, proposed contributions in the literature are discussed and the still existing challenges are presented.

2. Inland waterways management objectives

Inland waterways are large-scale networks composed of several interconnected navigation reaches (NR) (*see* Fig. 1). The main management goal is to maintain the water level of each reach around a setpoint: the Normal Navigation Level (NNL). Two boundaries are considered around the NNL and define the navigation rectangle: when the water level crosses one of these boundaries, the navigation has to stop. Due to the increase of navigation demand and the accommodation of the biggest ships, the navigation rectangle is restricted to several centimeters around the NNL.

To simplify the study of open-flow water networks, they are usually divided into reaches by considering initial and final ends, which usually correspond to hydraulic human-made devices such as gates or weirs. Three different kinds of reaches can be considered according to whether or not there are water streams leaving or entering such reach in an intermediate point: a reach with a tributary, when an external water stream flows into the considered navigation reach; a reach with a distributary, when a stream of water branches off from the navigation reach; and finally a *simple* reach, when there is neither a tributary nor a distributary. Fig. 2 depicts these three possibilities. Due to the configuration of the network, a navigation reach is a Multiple-Input-Multiple-Output (MIMO) system.

Each reach is linked with other reaches thanks to controlled gates and locks. In this way, the control of a gate or a lock located on a reach has a direct influence on the upstream and downstream reaches. The dynamics of the gates mainly depend on the water levels of the upstream and downstream reaches. They are located in the center of watersheds, and controlled or uncontrolled water exchanges occur between natural rivers and them. As an example, the Cuinchy-Fontinettes reach, located in the north of France, has more than 300 uncontrolled inputs or outputs that link it with the watershed. Finally, reaches are generally equipped with sensors that provide water level or discharge measurements. Thus, a waterway network is a strong interconnected MIMO system subject to uncertainties.

A reach is a large-scale system with complex nonlinear dynamics and variable time delays. It can be affected by resonance phenomena that causes waves from downstream to upstream (resp. upstream to downstream) with a magnitude of several centimeters. Depending on the magnitude of the waves, the attenuation of this phenomena might require several hours.

It is also known that leaks are present between two reaches due to the water-tightness problem of locks and gates. In addition, sensors and actuators are vulnerable to faults. The occurrence of faults can lead to an inefficient water level control and a waste of water resources, which is not acceptable in
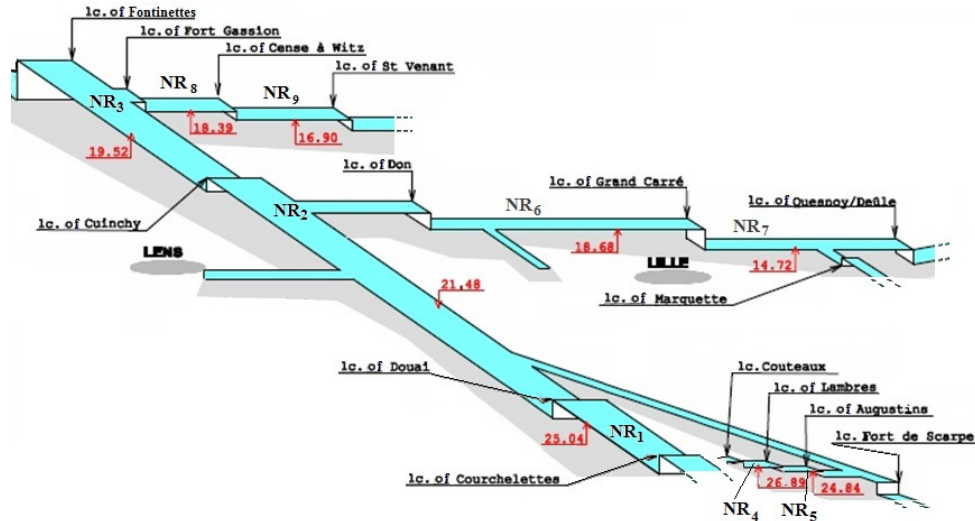
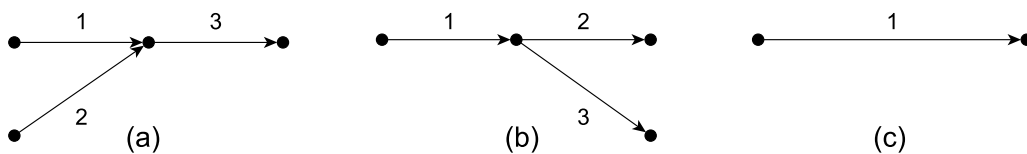**Figure 1.** Part of the waterways in the north of France composed of 9 NR.

Figure 2. (a) reach with a tributary, (b) reach with a distributary, (c) *simple* reach.

a context of climate change and increase of navigation demand. A decentralized FTC architecture is proposed to deal with this challenge.

3. Decentralized fault tolerant control architecture

The fundamental characteristics of the complexity of the presented case study are dimensionality and uncertainty, according to the author's research results in modeling and control. These two main features will be the overriding concern and will serve as major motivating factors for the development of decentralized control for this kind of studied systems.

This work only addresses the study of sensor faults. However, two other main kinds of faults can affect the system: actuator faults, when there is a mismatch between the specified control action and the action performed by the actuator; and system faults, when a change in the system dynamics occur. These two other types of faults are not considered in this work but will be addressed in the future.

Controllers aim at canceling the error between the measurements and their reference inputs. But when a sensor fault occurs, the faulty measurements directly corrupt the closed-loop behavior and may drive the system to its physical limitations or even to instability. To avoid or limit this behavior, FTC strategies that do not require any modification of the control law are proposed in [47, 66]. They are based on the conventional fault-tolerant configuration depicted in Fig. 3. The estimator provides y^{corr}, which is used
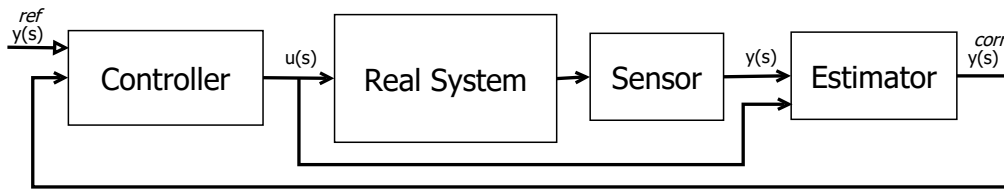
to estimate the fault-free sensor magnitude such as:

$$y^{corr}(s) = y(s) - f_y, \tag{1}$$

where s is the Laplace variable, $y(s)$ the output of the sensor and f_y an adaptive estimation of the fault magnitude that can be determined by:

$$f_y = g(u(s), y(s)), \tag{2}$$

where g is any nonlinear function and $u(s)$ is the controlled input.

Figure 3. Conventional Fault Tolerant Control configuration.

The estimation y^{corr} is then considered in the computation of the new control law, minimizing the effects of the faults.

Based on this principle, a decentralized FTC architecture is proposed in Fig. 4, whose purpose is to take into account large-scale interconnected systems. The real system is equipped with m actuators and n sensors, and a setpoint y^{ref} is attributed to each of the m controllers. According to the configuration of the network, consider that the global interconnected system can be described by (3).
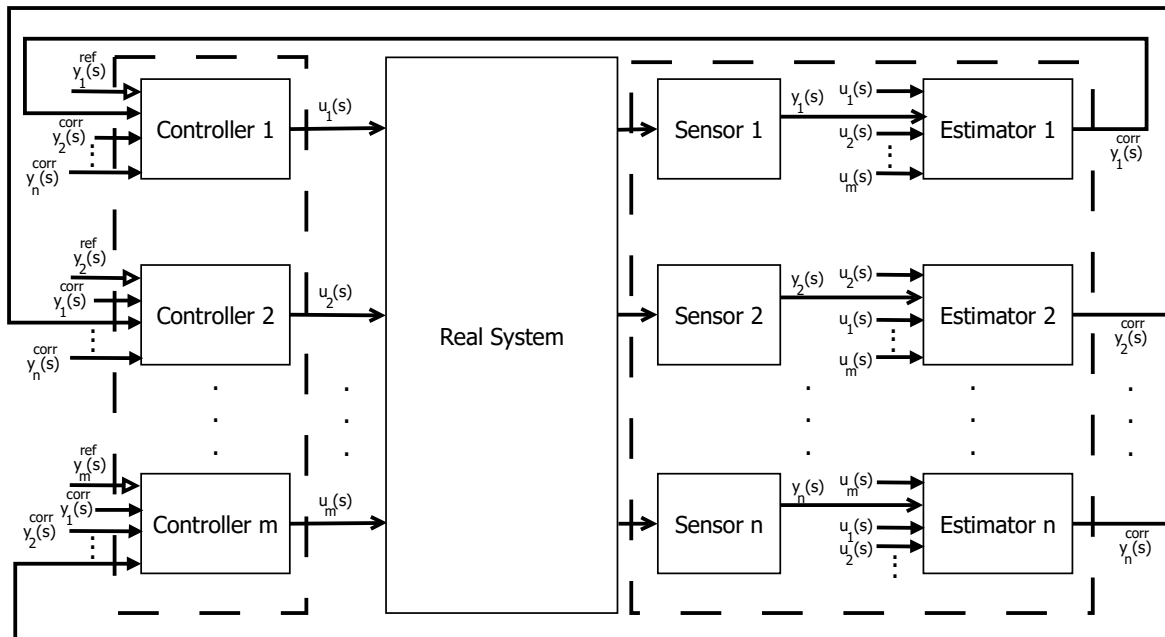
Figure 4. Decentralized fault tolerant control architecture.

$$\Sigma: \ \mathbf{Y}(s) = \ \mathbf{P}(s)\mathbf{U}(s), \tag{3}$$

where $\mathbf{P}(s)$ is the transfer matrix defined as follows:

$$\mathbf{P}(s) = \begin{bmatrix} p_{1,1}(s) & p_{1,2}(s) & \cdots & p_{1,m}(s) \\ p_{2,1}(s) & p_{2,2}(s) & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ p_{n,1}(s) & p_{n,2}(s) & \cdots & p_{n,m}(s) \end{bmatrix} \tag{4}$$

The structure of the elements of $\mathbf{P}(s)$ is given in the next section.
Therefore, the feedback system Σ_{cl} consists of:

$$\Sigma_{cl} : \begin{cases} \text{Plant } \Sigma : \mathbf{Y}(s) = & \mathbf{P}(s)\mathbf{U}(s) \\ \text{Controller } \Lambda : \mathbf{U}(s) = & \mathbf{K}(s)\mathbf{E}(s) \\ \text{Feedback } \Pi : \mathbf{E}(s) = & \mathbf{Y}^{ref}(s) - \mathbf{Y}^{corr}(s) \end{cases} , \tag{5}$$

where matrices $\mathbf{P}(s)$ and $\mathbf{K}(s) \in \mathbb{R}(s)$ have dimensions $n \times m$ and $m \times n$, respectively, and belong to the set of real rational matrices, and $\mathbf{Y}^{ref}$ is the set of the objectives.

The global interconnected system can be decomposed as:

$$\Sigma_{cl} : \begin{cases} \Sigma_i : y_i(s) = & p_{ii}(s)u_i(s) + \sum_{j=1}^{m} p_{ji}(s)u_j(s) \\ \Lambda_j : u_j(s) = & K_{jj}(s)e_j(s) + \sum_{i=1}^{n} K_{ij}(s)e_i(s) \\ \Pi_i : e_i(s) = & y_i^{ref}(s) - y_i^{corr}(s) \\ \quad \text{for } i = 1, 2, ..., n, \ \ j = 1, 2, ..., m, \text{ and } j \neq i \end{cases} , \tag{6}$$

where $p_{ii}(s)$ and $K_{ij}(s)$ are sub-elements of $\mathbf{P}(s)$ and $\mathbf{K}(s)$ respectively.

The ith term $\sum_{j=1}^{m} (p_{ji}(s)u_j(s))$ models the effect of all inputs on the measurement point i, with $i \neq j$. It represents the weighting interconnection values used to model the strength of interconnections. The jth term $\sum_{i=1}^{n} (K_{ij}(s)e_i(s))$ is the contribution of all errors between $y_i^{ref}(s)$ and $y_i^{corr}(s)$ in the computation of the control law for the actuator j, with $j \neq i$. In both cases, the elements that have to be taken into account depend on the configuration of the network. In Fig. 4, all elements ($y_i^{corr}(s)$ resp. $u_j(s)$) are considered as inputs of the blocks *Controller* and *Estimator* by default, but some of them might not be considered, depending on the configuration of the network.

Hence, it is necessary to determine these interconnections according to the dynamics and the configuration of the network. A modeling approach has to be proposed to obtain this information as well as the transfer matrix $\mathbf{P}(s)$ defined in (4). Therefore, it is necessary to develop decentralized control algorithms. Finally, the adaptive estimators have to be designed according to FDI methods. The ongoing work on each of these three topics is described hereinafter.

4. Modeling of inland navigation networks

As water networks are large-scale systems, they are usually decomposed into reaches to simplify the study. Reaches are generally defined as parts of a water stream that are comprised between a beginning and an ending point. These points generally correspond to the location of hydraulic structures that clearly delimit the water course, but they might as well be chosen due to topological reasons. Thus, water networks are regarded as the connection of individual reaches.

Following this idea, the first question that arises is which is the most suitable way to obtain an accurate mathematical representation of the open-flow canal system. The real behavior of the reaches

can be accurately described by the Saint-Venant equations [11]. However, as there is no known analytical solution for these equations and they are strongly sensitive to errors in the geometry and other unmodeled dynamics, simplified models are used instead [8]. Some examples are the Integrator Resonance model (IR) [23,62], the Integrator Delay model [58], the Integrator Delay Zero model (IDZ) [34] and Gray-box model [13,22].

The IDZ model is chosen due to its capability to characterize the dynamics of the system in all regimes with great accuracy. Its structure is as follows:

$$p_{ij}(s) = \frac{\alpha s + 1}{\mathscr{A} s} e^{-\tau s}, \tag{7}$$

where α represents the inverse of the zero, $\mathscr{A}$ the integrator gain and τ the propagation time delay. The exact values of these parameters cannot be computed; however, they can be accurately approximated as shown in [34]. Since the used parameters are an approximation of the theoretical ones, the notation $\hat{p}_{ij}$ replaces p_{ij}.

In low frequencies, the canal is close to a tank-like behavior, with the integrator term reproducing this phenomenon, which can be approximated by the backwater area inverse. On the other hand, the delay represents the minimum time that a wave requires to travel from its origin to the measurement point. Assuming that the wave velocity V and the wave celerity C_w are constant, τ_d (perturbation generated upstream and measured downstream) and τ_u (perturbation generated downstream and measured upstream) can be computed in the following fashion:

$$\tau_u = \frac{L}{C_w - V} \tag{8a}$$

$$\tau_d = \frac{L}{C_w + V} \tag{8b}$$

where $C_w = \sqrt{g\mathscr{A}/T}$ and $V = q/\mathscr{A}$, with L the total length of the reach (m), g the gravitational acceleration (m/s^2), $\mathscr{A}$ the section (m^2), T the top width of the canal section (m) and q the discharge (m^3/s).

On the other hand, the zero, whose calculation procedure is omitted here but can be found in detail in [34] along with the other parameters, accounts for the high frequency dynamics. When the three elements are merged, a model that provides fitting accuracy in the whole frequency range is obtained.

With all that, (7) is used to model the different reaches that compose the overall system. By considering a reach with measured depths $y(0,s)$ and $y(L,s)$ and discharges $q(0,s)$ and $q(L,s)$—where 0 and L are the upstream and downstream ends of the reach, respectively—, the following transfer function matrix $\mathbf{P}_r(s)$ links these variables for the rth reach of the network in the following way:

$$\begin{bmatrix} y(0,s) \\ y(L,s) \end{bmatrix} = \underbrace{\begin{bmatrix} \hat{p}_{11}(s) & \hat{p}_{12}(s) \\ \hat{p}_{21}(s) & \hat{p}_{22}(s) \end{bmatrix}}_{\mathbf{P}_r(s)} \begin{bmatrix} q(0,s) \\ q(L,s) \end{bmatrix}, \tag{9}$$

where the $\hat{p}_{ij}(s)$ elements of matrix $\mathbf{P}_r(s)$ follow the IDZ model introduced in (7). Considering that the total number of reaches in the whole network is $\mathscr{R}$, $\mathbf{P}_r(s)$ can be computed, with $r = 1, ..., \mathscr{R}$.

Individual matrices $\mathbf{P}_r(s)$ are embedded into matrix $\mathbf{P}(s)$ defined in (4) in the following fashion: each $\hat{p}_{ij}(s)$ term of matrices $\mathbf{P}_r(s)$ is carefully placed inside $\mathbf{P}(s)$ according to the input-output (I/O) pair (u, y) that it links. Of course, not all possible (u, y) pairs are linked, hence $\mathbf{P}_r(s)$ contains null elements that account for such reason.

The final goal is to check the accuracy of such IDZ models by comparing them with the real behavior of the canal. To do so, two main options are considered. The first one consists in using an hydraulic software that enables the modeling and simulation of waterways: for this purpose, SIC^2 [3], a commercial

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[3] http://sic.g-eau.net/

software, is chosen. The second approach is based on using available data from the real system. However, these data need to be previously treated or filtered due to the presence of a large number of uncertainties in the network.

5. Decentralized control approaches

Control approaches for free-surface water systems have been widely proposed in literature [36,39]. Most of them are dedicated to irrigation canals [28, 37, 49, 53, 63]. In [21, 55, 56], decentralized control techniques have been conceived for interconnected irrigation pools. The possible destabilization of decentralized controllers is addressed in [57], and the use of decouplers is suggested. When analyzing the coupling of the subsystems, [38] also studied the coupling effects and the possible decouplers. Decentralized control using decouplers is implemented in [40]. In [46, 50], a distributed Model-based Predictive Control based on multi-agent systems applied to interconnected irrigation pools is proposed with the main objective to overcome the computational effort of centralized control techniques.

More recently, control algorithms have been proposed for inland navigation reaches by taking into account their characteristics such as resonance, no significant slope or locks [24,27]. These contributions are focused on a single navigation reach. A decentralized control algorithm has been proposed in [51] considering interconnected inland navigation reaches.

In decentralized control, there are two main approaches to deal with the problem of interconnections [35]. The first one is the passive approach, where a decentralized control is designed for each isolated subsystem for certain desirable performance and the design is independent of the knowledge of the interconnections; the control is then applied to the overall system [59]. The second one is the synthetic approach: in this case, interconnections are explicitly taken into account when designing the controllers [20]. There is a large number of survey papers [10,54] and books [19,32] that provide further information on decentralized control theory and practice.

With regard to the global interconnected system given by (6), consider Γ as a weighting matrix of positive values used to model the strength of the interconnection between subsystems i and j. This interconnection matrix can be defined in the following manner:

$$\Gamma_{ij} = K_{ij}(s)e_i(s). \tag{10}$$

Considering that the gains of the controllers have a strong interaction, the mathematical relationship of input/output pair that describes the control problem is the following:

$$u_j = -(K_{j,j}(s)e_j(s) + \sum_{i=1}^{n}\Gamma_{ij}) \text{ with } j \neq i \text{ for } j = 1,...,m \tag{11}$$

such that controller K exists and its diagonal blocks are m separate controllers defined by:

$$K = diag\left(K_{jj}\right), \ \ \forall j = 1,...,m \tag{12}$$

In other terms, the problem consists in computing the controller K which stabilizes the global system (3) according to any specific feature. Indeed, the main idea is to design a feedback controller in such a way that the stability of the closed-loop system can be guaranteed for a wide range of uncertainties in the structure and subsystems dynamics. Thus, a special attention should be paid to the domain of uncertain systems.

On the other hand, the decentralized control strategy is naturally appended with the global control, whose role is to enhance the dominance of subsystems' stability by reducing the effect of the interconnections. Then, a condition for stability of the overall system can be proposed by using aggregated information about subsystems and interconnections. This condition requires that the system remains stable under any structural perturbation. So, in a few words, this work should lead to the generation of an algorithm capable of designing decentralized control laws for robust stabilization of uncertain interconnected systems by using and extending the works in [45,65].

6. Fault detection and isolation methods

Due to the fact that waterways are large-scale systems, a large number of sensors and actuators are placed throughout the whole system in order to collect data and to operate the hydraulic equipment, respectively. However, these devices are not perfect but are subject to measurement errors and faults. This fact justifies the need for tools or procedures that are able to detect the occurrence of a fault. But just knowing that the system is in a faulty situation is usually not enough, since the faulty element needs to be addressed in order to go back to the nominal behavior.

FDI allows the user, under certain circumstances, to detect whether or not a fault appears in the system and to be able to isolate it from the rest of possible faults, that is, to identify in which component the fault occurs. Many different diagnosis methods exist, but they all follow the principle of consistency [7]. First, the nominal behavior of the system is characterized by means of a plant model. Next, it is checked whether the measurement information (U, Y) (I/O pair) and the nominal behavior are consistent: if so, no inconsistency is detected, even if a certain fault exists. Moreover, it is possible that two (or more) different faults cause the same I/O pair, and thus an ambiguity in the diagnostic result exists. Hence, it is possible to detect a fault with only information about the nominal behavior of the system.

Conditions about the detection of a fault have just been given, but fault isolation and identification are two other crucial aspects. To address them, information about the faults and their impact on the system are needed, which means that fault models are required. But of course, this information is not always enough to isolate a fault, since more than one fault may generate the same effect, which means that, again, an ambiguity is present.

Many application examples of FDI can be found for water systems. A brief survey of these works include FDI using model-based set-membership applied to open-flow channels [25], decentralized FDI of a water transport network [48], an application to drinking water networks [52], the development of a new FI architecture for irrigation canals [41], FDI for irrigation canals for time-varying delayed systems [4] and the development of algorithms for leak detection in open-flow water channels [5].

There are two main approaches used to solve the fault detection and isolation problem [60]: model-based and data-driven methods. The model-based FDI approach compares the measured data with the estimated data from the knowledge of the nominal behavior of the system. This comparison generates a residual, which is an expression that is close to zero when no fault is present in the system and that diverts from zero when a fault occurs. However, since it is necessary to compute a model that represents the normal behavior of the plant in order to contrast the measured data, a deep knowledge of the physical principles that take part in the system is required.

On the other hand, data-driven methods rely on the usage of experimental data, and no previous physical knowledge of the system is needed. The main idea is to build a classifier that is able to localize in which component the fault occurs [18]. However, the main drawback of this approach is that the applicability of this problem is restricted by the available data. This means that only past faults may be detected, as they are the only ones that have been experimented by the system.

The selected approach to this problem is a blend between both model-based and data-driven methods. The idea is to obtain a fairly accurate model built from the physical equations that govern the system. With this model, residuals can be generated by comparing the nominal value to the measured data. Afterwards, a classification problem can be solved by considering these residuals and a set of labels. Therefore, by combining the two methods, it is possible, to some extent, to take advantage of the best features and to avoid the main drawbacks of each methodology.

7. Conclusion

This paper presented the ongoing research in the topic of decentralized fault-tolerant control applied to inland navigation networks in the framework of an increase in the water demand. The main problems for water management in the topics of modeling, control, FDI and FTC were discussed, and a survey of tools and references in the literature was detailed. The inland waterways in the north of France served to illustrate the work.

The mid-term work plan consists in comparing the theoretical IDZ models with the results provided by an hydraulic simulation software and by a computed model from real data to check the accuracy of the former. This verification seeks to obtain reliable models that will later be used for control strategies such as Model Predictive Control (MPC), FDI and FTC. For FTC, only sensor faults are considered at the present time, but actuator and system faults will also be considered and addressed.

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