# CENTAUR: Cost Effective Neural Technique for Alleviation of Urban flood Risk

## *Deliverable 2.4: Report on redundancy and impacts of data uncertainty*

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| | | | | | |

## Acronyms

| USFD | UNIVERSITY OF SHEFFIELD |
|---|---|
| EMS | ENVIRONMENTAL MONITORING SOLUTIONS |
| UoC | UNIVERSIDADE DE COIMBRA |
| EAWAG | *EIDGENOESSISCHE ANSTALT FUER WASSERVERSORGUNG ABWASSERREINIGUNG UND GEWAESSERSCHUTZ* |
| VE | VEOLIA |
| AC | AC AGUAS DE COIMBRA EM |

## Acknowledgements

## Executive Summary

This report has been produced as part of the Cost Effective Neural Technique for Alleviation of Urban Flood Risk (CENTAUR) project, funded by H2020 under grant agreement number 641931. It corresponds to Deliverable 2.4: *Report on redundancy and impacts of data uncertainty and likely benefits of CENTAUR following virtual study*, from Work Package WP2: *System Control and Software Development*.

This reports aims at refining the sensing/data collection strategy, taking into account concepts of data redundancy for system resilience and impacts of data variability on the effectiveness of control solutions.

The report is divided in two main parts. The first part presents a Failure Mode and Effect Analysis (FMEA), in which the main failure modes and their causes are identified, contributing to the risk analysis of the Centaur system failure. In the second part, the analysis of the impact of data uncertainty/ variability is conducted; this analysis focuses on the influence of the location of the data sensors towards the performance of the flow gate actuator.

The FMEA analysis conducted helped to identify some of the potential failure modes of the Centaur gate. The presented FMEA has had input from project partners, but will be further discussed at the next General Assembly meeting to be held in Coimbra (25 and 26 October 2016). Based on the FMEA, the most relevant are related to energy supply interruptions. This type of failure seems to potentially have a significant role in the reliability of the Centaur system. Therefore, particular attention should be paid to energy supply issue during the development of the Centaur system.

The results obtained from the investigations carried to study the effect of data uncertainty/ variability and the influence of the location of the data sensors towards the performance of the flow gate actuator showed that a model-free reactive controller presents two undesired behaviours, namely signal delay intolerance and actuation chattering.

# CONTENTS

# 1 Introduction

## 1.1 Deliverable objectives

This report is part of Cost Effective Neural Technique for Alleviation of Urban Flood Risk (CENTAUR) project, funded by H2020 under grant agreement number 641931. It corresponds to Deliverable 2.4: *Report on redundancy and impacts of data uncertainty and likely benefits of CENTAUR following virtual study* from WP2: *System Control and Software Development.*

This report summarises the work conducted by Eawag towards identifying the impacts of data uncertainty/ variability and quantification of benefits of a functional pilot CENTAUR. It aims at refining the sensing/data collection strategy, taking into account concepts of data redundancy for system resilience and impacts of data variability on the effectiveness of control solutions.

The report is divided in two main parts. The first part presents a Failure Mode and Effect Analysis (FMEA), in which the main failure modes and their causes are identified, contributing to the risk analysis of Centaur system failure and to highlight the impact and need for sensor redundancy. In the second part, the analysis of the impact of data uncertainty/ variability is conducted; this analysis focuses on the influence of the location of the data sensors towards the performance of the flow gate actuator and the effect of sensor uncertainty on flood actuator.

## 1.2 Partners involved in this deliverable

This report was prepared mainly by the team of Eawag researchers: João P. Leitão, Juan Pablo Carbajal, Luís M. de Sousa and Jörg Rieckermann. All project partners have been asked to contribute to the identification of failure modes, failure causes and to the assignment of values to each failure mode Severity, Likelihood of Occurrence and Detection indices.

## 1.3 Structure of the report

This report is organized as follows. In Chapter 2 the potential failure modes of the Centaur flood control gate are identified, based on the results of a Failure Mode and Effect Analysis (FMEA). In Chapter 3 the results of the influence of the location of the data sensors (water level sensors) on the quality of the control of the Centaur flood gate are presented. In Chapter 4 the main conclusions of the two analyses presented in the previous chapters are presented.

## 2  Failure Mode and Effect Analysis (FMEA) of the Centaur system

### 2.1  General: *what is an FMEA?*

**Concepts and objectives of FMEA**

FMEA (Failure Mode and Effect Analysis) was one of the first structured methods for failure analysis. It allows the analysis of the various failure modes, their causes and effects in a systematic way (Sobral, 2012). It can also be defined as an engineering tool to define, identify and eliminate known faults and potential problems of a system design or process before it is fully deployed and used (Stamatis, 2003). Teoh and Case (2004) define the FMEA as a technique that helps identifying the potential failure modes of a product or a process, and the effects of the failures, and also providing basic information about the expected reliability of the product or process. According to Moura (2000), FMEA is based on the following set of objectives:

- Recognize and evaluate the potential failure of a product/ process and its effects;
- Identify actions that could eliminate or reduce the chance of potential failure modes;
- Document the analysis process.

**Benefits and limitations of FMEA**

Performing an FMEA contributes to understanding the potential problems of products and processes. An FMEA helps devising a system of priorities for improvement, investment, development and testing. According to Lipol and Haq (2011), an FMEA leads to various benefits, which some can be directly related to the development of the Centaur system:

- Greater reliability, quality and safety of the Centaur system;
- Systematic identification and elimination of potential failure modes of the Centaur system;
- Cost reduction of Centaur system production and operation;
- Help in the development of Centaur control plans;
- Provides a well-documented record of improvements and corrective actions (to be) implemented and new ideas for improvement on future versions of Centaur.


Although the FMEA method has been shown to be one of the most important preventive measures during the design phase of a system, product, process or service, the method has some limitations:

- The analysis can be very detailed making it a tedious and time consuming activity, resulting in high implementation costs;
- The method is not adequate to explore complex failure modes involving multiple failures. For these cases, other methods, such as the Fault Tree Analysis method, are more adequate (Riplová, 2007);
- FMEA depends on the degree of experience and team opinions, which limits the resolution of any problem beyond empirical knowledge;

- The relative importance of Severity (Sev), Occurrence (Occ) and Detection (Det) indices is not taken into account, i.e., it is assumed that the three factors are of equal importance, which often does not correspond to the reality (Liu et al, 2011);
- Different classifications of Sev, Occ and Det indices can produce exactly the same Risk Priority Number (RPN) value, but the consequences of the hidden risks can be totally different. For instance, two situations with values of 2, 3 and 2 and 4, 1 and 3 for Sev, Occ and Det indices, respectively, will result in the same RPN value; however the implications of the hidden risks can be quite disparate due to the different degrees of severity of the failure mode (Liu et al, 2011);
- RPN considers only three factors in terms of safety disregarding other important factors, such as economic factors (Liu, et al., 2011).

Despite the limitations of FMEA, it is still commonly used to help improving systems (or products) resilience to failures of various causes. For this reason, an FMEA was conducted for the development of Centaur. Such analysis is presented in the following sub-section.

## 2.2   The FMEA of the Centaur system

The study presented in this report considers only isolated failures. It does not take into account multiple failure scenarios (with multiple events). In this case, other tools to estimate risk of failure, e.g., Fault Tree Analysis and/or Event Trees, should be employed to determine exact probability and risk levels.

**Definition of the Severity, Likelihood of Occurrence, Detection indices**

One of the first steps in a FMEA is to define the various indices scales; these are presented in the following paragraphs.

*Severity (Sev)*. The severity (Sev index) represents the negative impact caused by the failure mode. In FMEA the analyst is required to define the range of the Sev index. This index may vary between 1 and a pre-defined maximum value, e.g., 5 or 10. In this study, five classes of severity were considered, as presented in Table 1.

Table 1. Severity index classes used in the Centaur FMEA analysis

| Severity index (Sev) | Meaning |
|---|---|
| I (1) | Not relevant or very minor: only results in a maintenance action |
| II (2) | Minor: affects very little of the system |
| III (3) | Moderate: mostly financial damage due to a Centaur failure (e.g., damage to the Centaur system and to the network nearby infrastructure) |
| IV (4) | Critical: causes a loss of primary function (e.g., stops flooding protection) |
| V (5) | Catastrophic (product becomes inoperative; the failure may result in complete unsafe operation and possible deaths. E.g., possible flooding in unexpected locations) |

*Likelihood of occurrence (Occ).* The likelihood of occurrence index consists of the likelihood (or probability) of the potential cause. The likelihood can be estimated based on component/ system failure analysis, failure modelling, empirical knowledge, etc. In this study, a five class index was used, as presented in Table 2.

Table 2. Likelihood of occurrence index classes used in the Centaur FMEA analysis

| Likelihood index (Occ) | Meaning |
|---|---|
| A (1) | Extremely Unlikely (Virtually impossible or not known occurrences on similar products) |
| B (2) | Remote (relatively few failures) |
| C (3) | Occasional (occasional failures) |
| D (4) | Reasonably Possible (repeated failures) |
| E (5) | Frequent (failure is almost inevitable) |

*Detection (Det).* The detection index (Det) consists of the evaluation of the failure detection effectiveness. In this study, this index is defined in a scale of five classes: from 1 ("*Certain or almost certain*") to 5 ("*Fault is undetected*"); the five classes are presented in Table 3.

Table 3. Detection index classes used in this study.

| Detection index (Det) | Meaning |
|---|---|
| 1 | Certain (fault will be caught on test) or almost certain |
| 2 | High |
| 3 | Moderate |
| 4 | Low |
| 5 | Fault is undetected by Operators or Maintainers |

*Risk Priority Numbers (RPN).* The objective of Risk Priority Numbers (RPN) is to prioritise the identified failure modes. RPN result from the product of the three above mentioned indices: Severity (Sev), Likelihood of occurrence (Occ) and Detection (Det).

$$RPN = Sev \times Occ \times Det$$

In the specific case of this study, since the three indices (Sev, Occ and Det) vary between 1 and 5, the RPN will vary between 1 and 125.

## Centaur failure modes

The identification of potential failure modes will have contributions from all the Centaur project partners (USFD, EMS, Steinhardt, UoC, EAWAG, VE and AC). The partners have been asked to think and suggest potential failure modes. So far, the empirically identified potential failure modes of the Centaur system are the following:

A. Bad sensor data in one or more Level Monitoring Sites (LMSs)
B. Loss of communication link between the Communication and Control Hub (CCH) and one or more LMSs
C. Loss of communication link between CCH and Flow Control Site(s) (FCS)
D. Flow control device stops responding due to mechanical problems

The FMEA tables are presented in Appendix I. The table reflects the view from the partners about what can go wrong with the Centaur system, and highlights the most relevant (higher risk) failures that can occur. Interestingly, the more relevant causes of failure are related to energy supply interruptions:

- *Interruption of energy supply to the gate (FCS),* RPN = 64, and
- *Interruption of energy supply to sender/ receiver of Communication and Control Hub (CCH),* RPN = 48.

The consequences of these two causes of failure range from a complete inability of the Centaur system to mitigate flooding to a sub-optimal flood protection. As a result, energy supply seems to play a significant role in the reliability of the Centaur system. Therefore, during the development of the system a particular attention should be paid to energy supply issue, especially, if possible, towards increasing the detection of energy supply interruptions.

# 3 Analysis of data and drainage system uncertainty and variability

## 3.1 General

The proposed control of the Centaur flood gate is based on a set of pre-defined rules of upstream and downstream water level measurements, which do not include knowledge about the physical conditions of the sewer, e.g. a mathematical model. This means that control actions are taken based on current sensor information following a cleverly predefined set of discrete rules (e.g., based on the fuzzy logic concept) or an algorithm (e.g., PID: Proportional–Integral–Derivative). This is the simplest and cheapest controller family that could be implemented in the Centaur system.

In the subsequent analysis, a template reactive controller (a PID controller) is considered. The output of the PID is limited to the [0, 1] range (with limited integral windup), and represents the position of the controlled flood gate. The PID uses a water level sensor signal and a set point value for it to generate control actions. In this situation, there are two signal features that might influence the quality of the control: (i) the inherent delay between the level signals, which is related to the distance between the water level measurement sensors and the gate, and (ii) the uncertainties associated with every measurement, in this case the water level sensor uncertainties generated by intrinsic signal variability (changes in water level) and signal noise (sensor and communication noise).

In order to study the influence that these features have on the controller's performance, a simple numerical model was developed. It is based on a series of connected reservoirs (Figure 1), with a level sensor located at the most downstream reservoir and a single controlled gate located at some upstream position (position 3 in Figure 1). Water comes into the chain at reservoir 1.
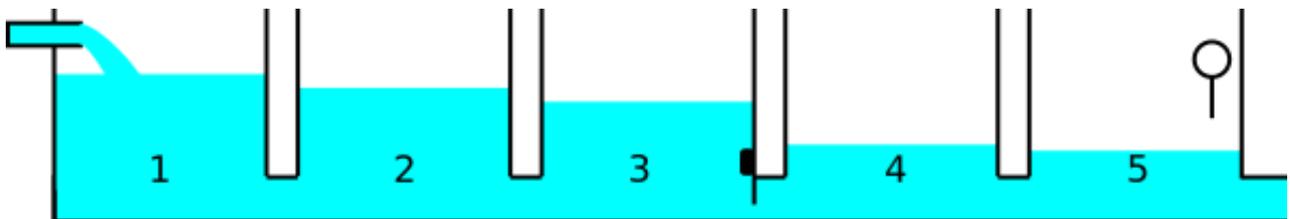


Figure 1. Model used to investigate the influence of the location of the water level sensors in relation to the flood control gate. The gate is shown in position 3 and the level sensor in reservoir 5.

In the following sub-sections, the results of the investigation done using this model and controllers are presented.

## 3.2 Effects of distance between water level sensor and Centaur flood gate

To study the influence of the distance between the water level sensors and the flood gate on the quality of the control, the numerical model was assembled with five connected reservoirs (as in Figure 1). During all simulations the objective was to keep constant the

level of the most downstream reservoir (reservoir 5). Three scenarios were considered in which the controlled gate location is downstream of reservoir 1, 3 and 4, respectively.

Figure 2 shows the results of the various scenarios. For each gate position the controller was tuned for maximum performance. The results show that for the given reactive controller, intrinsic delay make the control task more difficult the more distant the sensor is to the gate.
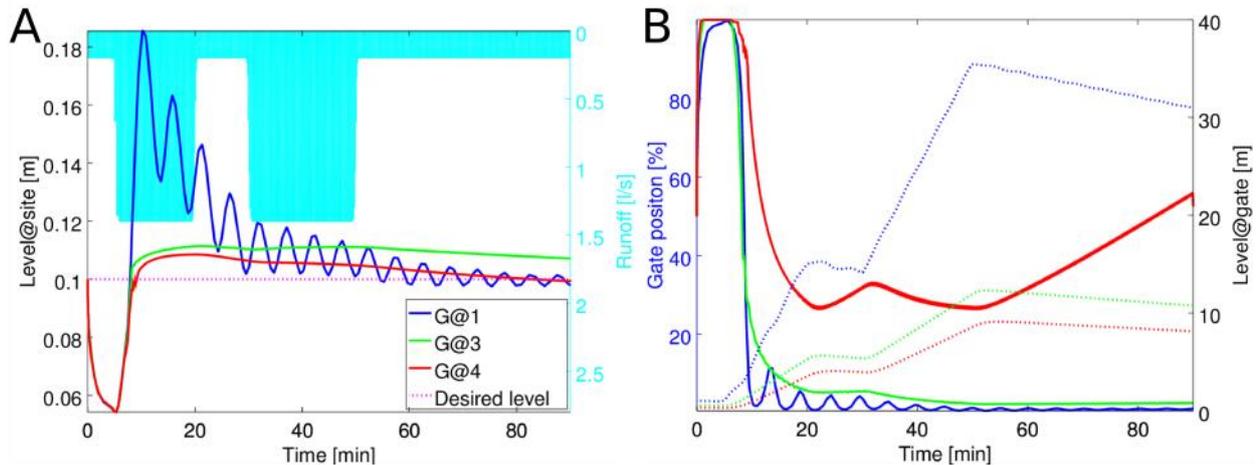


Figure 2. Results obtained for the three scenarios. The labels indicate the locations of the gate in each scenario, e.g. G@1 is gate at outlet of reservoir 1. Panel A shows in solid lines the level at reservoir 5 (the controlled quantity). Water coming into the reservoir chain is shown in a secondary axis (to the right). Panel B shows the gate position for each scenario in solid lines and the level at the reservoir where the gate is located in dotted lines (secondary axis).

Moreover, the levels reached by the water in the reservoir where the gate is located increase with the sensor-to-gate distance (dotted lines in Figure 2, panel B). This highlights for the fact that although a gate reduces the risk of flooding in reservoir 5 (water level close to desired value), this risk may increase at the reservoir where the gate is located. The PID used in this set-up is single objective, which is a simplification of the PID to be implemented in Centaur. The latter is a multi-objective Fuzzy PID that, in addition to upstream water level, also considers the downstream level to operate the gate; so one would expect a slightly different behaviour from that presented in this study. However, because the direct effect of closing the gate is an increase of the upstream water level, the risk of flooding upstream is also likely to increase.

The reduced performance of the controller in distant sensor-to-gate situations is due to early reaction of the controller: its actions take some time to affect the sensor value downstream. Hence, the controller needs to compensate for the errors that its premature actions induce, delaying the convergence to the setpoint and generating oscillations due to over-compensation. This is explained by the interaction between the derivative and the integral terms. The gains of each were optimized, but how they relate to each other was not studied. The assumption is that the derivative term reacts to delayed information (inducing oscillations, irrespective of the actual error value) and the integral terms brings

these oscillations around the desired value. The integral term is always "slow", even more in this PID because of the windup.

## 3.3   Impact of data variability on Centaur flood gate controllability

To evaluate the influence of data variability in the control of the Centaur flood gate, the model presented in Section 3.1 was assembled with only two connected reservoirs with the gate controlling the passage of water from one reservoir to the other. Two scenarios were considered to evaluate the impact of the data variability on the control of the gate. One, unrealistic, considers that the data has no variability (Scenario a); the other, more realistic, considers that data from the water level sensors has some variability (Scenario b). Data variability is simulated using Gaussian noise. The dynamic equations are integrated using the Euler–Maruyama method.

The simulated scenarios consider a control task in which the desired level of Reservoir 1 (upstream) is reduced to avoid flooding due to incoming water spikes. In both scenarios we investigated two controllers, the same PID controller as in the previous sub-section and a lookup-table based controller. The latter selects the gate position based on a predefined set of values created off-line. These values define a mapping between the desired level and the gate position. We programmed a dynamic transition between these values: if the desired water level is lower than current, first fully open gate and then slowly set the table value. This lookup-based controller highlights the advantages of a reactive controller (Figure 3), but also illustrates the almost null effect of the added noise in the control performance (Figure 4).

**Scenario a (data with no variability)**

Figure 3 shows the results for both controllers. In this case the PID controller is able to follow the change in the desired water level, even in the presence of a very strong spike in the water input (top-left panel). At this point the controller struggles to keep the desired level but is able to follow the desired level within a short period of time. As expected, the lookup-table based controller cannot cope with the changes in the water input and only attains the desired level after the input event is over. Both controllers actuate the gate smoothly and only when necessary (bottom panel).

Figure 3 also shows how the PID reacts to the incoming water peak (around 140 min.) by fully opening the gate to keep the local water level at the desired value, while the lookup-table controller is unable to deal with this sudden change in the input. The PID's action raises the downstream water level, and might increase the downstream risk of flood, especially if in the real site there were downstream uncontrolled tributary sewers. This risk would be even higher when water level variability is present, as demonstrated in the following paragraph (Scenario b).
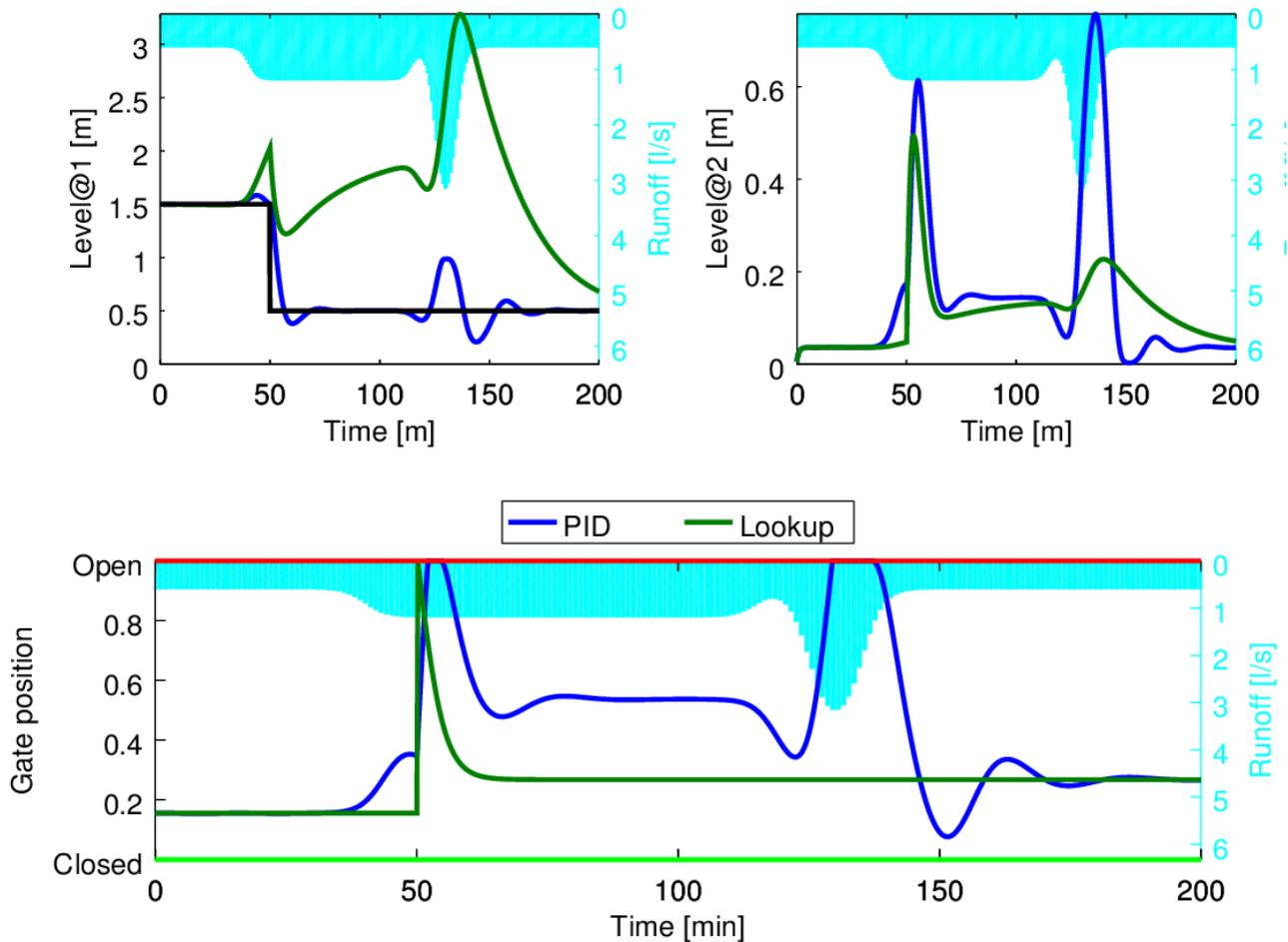
Figure 3. Control performance of reactive (PID) and lookup-table controllers with noiseless signals. Without variability, the reactive controller is able to track the level set point with smooth actuation. The lookup-table based controller is unable to cope with varying water inputs (black line represents the setpoint level).

## Scenario b (data with noise)

Figure 4 shows the results of the same controllers when the water input has random variations, which are propagated to the water level. As before the lookup-table based controller cannot cope with the input event, but the level follows a similar trajectory as in the previous case (plus noise). The PID is able again to maintain water levels close to the desired values but it reacts to the variability of the signal, producing a strongly varying actuation known as "chattering". Very strong filtering of the signal could reduce the chattering, increasing the complexity of the controller algorithm since the filter parameters need to be set and they might need to be adapted to different situations. This is a common problem in reactive controllers that can be dealt with using data variability models.
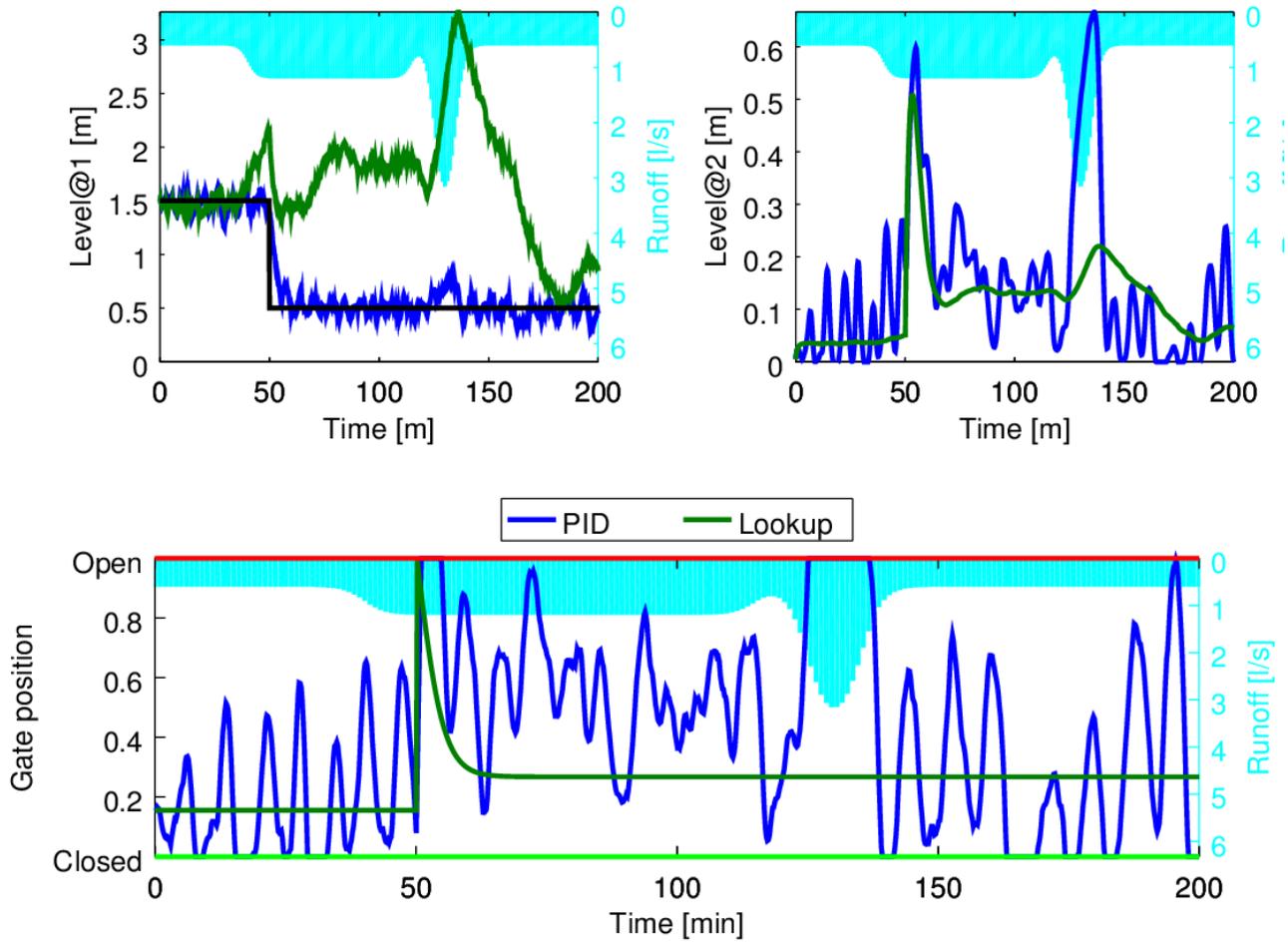
Figure 4. Control performance of reactive (PID) and lookup-table controllers with noisy signals. The reactive controller is able to track the level set point, but it reacts violently to small quick variations in the level.

# 4 Conclusions

## FMEA analysis

FMEA helps identifying the most important failure modes of Centaur. As a direct result of the FMEA, the most important failures, i.e., the failures with higher risk levels can be prioritised. The FMEA results contribute to adjust/ improve the development of the Centaur system, in order to reduce the risk of its operation, increasing its reliability.

A first list of potential failure modes and their severity was suggested: the priority failure modes are associated with energy supply interruptions and can strongly limit the impact of Centaur in flooding reduction. Therefore, this issue of possible energy supply interruptions should be addressed in detail during the Centaur system development process. Other high priority failure modes should also be addressed in order to make the Centaur system reliable as reasonably possible (e.g., cost-benefit analysis).

## Impacts of data variability and uncertainty in Centaur operation

The previous sections showed that a model-free reactive controller presents two undesired behaviours: signal delay intolerance (Sub-section 3.2) and actuation chattering (Sub-section 3.3).

Data coming from distant sensors needs to be fused correctly to be useful for making control decisions. The reactive controller featured in the previous sections had no knowledge about the source of the sensor signal. When the signal came from locations far away from the actuator, the controller had troubles coping with the signal delay (Figure 2) and it had to compensate for its too early reactions. To deal with this issue the signals need to be conditioned before being used for control. In this case signals would be synchronized to avoid untimely control actions – the rule-based controller would need to include the delay knowledge. This synchronization requires knowledge of the time of travel of the signal generating event, which could be yielded by a model of the site.

A reactive controller, having no model of the controlled site, is also unable to weight the consequences of its actions on the risk of flooding. As Figures 3 and 4 showed, the PID fully opened the gate to keep the local water level at the desired value, considerably raising the downstream water level, and therefore increasing the downstream risk of flood, especially if downstream there were uncontrolled tributary sewers. This situation might be undesired in a real installation, and the gate controller should keep both flood risk levels at bay. This is an impossible task using only local information, or without a higher level arbitration model.

Natural variations of a sensor signal might not be relevant for control performance, nevertheless reactive controllers as the ones shown here react to it and produce unnecessary control actions, i.e. chattering. This surplus actuation wastes energy and wears the actuators (flood gates), demanding more maintenance and increasing the risk of failure. To avoid the consequential unnecessary control actions, most reactive control systems include smoothing or filtering of the input and output signals. Implementing these smoothing stages requires additional parameters (e.g. Cut-off frequencies, correlation

lengths, etc.), thus increasing the complexity of the controller. In the specific case of fuzzy rule-based controllers, optimised membership functions can deal with the noise to some extent; but the range of the optimisation procedure needs to be defined a priori, either based on expert knowledge (if available, and correct) or based on results from physically-based simulators.

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# Appendix I. FMEA table

Tables I.1 and I.2 structure the FMEA analysis, aiming at support the development of the analysis and to identify the most important failure modes, based on the higher Risk Priority Number (RPN). The classes of the Sev (severity), Occ (Likelihood of occurrence) and Det (Detection) for each potential failure mode should be filled using the class definitions presented in Section 2.2.

Table I.1: FMEA of the Centaur system (Data collection and transmission function)

| Name / Function | Potential failure mode | Potential effect(s) of failure | Sev | Potential cause(s) of failure | Occ | Detection Mode | Det | RPN |
|---|---|---|---|---|---|---|---|---|
| A. Data collection and transmission (sensors) | **Bad sensor data on one or more Level Monitoring Sites (LMSs)** | Communication and Control Hub (CCH) sends 100% open control signal to Flow Control Sites (FCS or gate) with **potential** (if there is a large volume of water stored) **to cause downstream flooding**. | 4 | Two or more sensors on LMS outside measuring range. | 3 | Two or more sensors on LMS outside measuring range. | 1 | **12** |
| | | | 4 | Three sensors on LMS have significantly different measurements. | 3 | Three sensors on LMS have significantly different measurements. | 1 | 12 |
| | | CCH sends chattering command signals to FCS (gate). **Sub-optimal flood protection control.** | 2 - 3 | Noise level too high on sensor due to ageing, damage or noisy working conditions. | 4 | Observation of chattering or sensor noise increasing. | 3 | **24 - 36** |
| | | | 2 - 3 | Problem with the algorithm. | 3 | Observation of chattering. | 3 | **18 - 27** |
| | **Loss of communication link between CCH and one or more LMSs** | FCS (gate) stays at current opening position. **Sub-optimal flood protection control.** | 2 - 3 | Interruption of energy supply to sender/ receiver on CCH. | 4 | | 4 | **32 - 48** |
| | | | 2 - 3 | Malfunction of sender/ receiver on CCH. | 3 | | 4 | **24 - 36** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 2 - 3 | Interruption of energy supply to sender/Receiver on LMSs. | 5 | CCH does not receive data | 2 | **20 - 30** |
| | | | 2 - 3 | Malfunction of sender/receiver on LMSs. | 3 | CCH does not receive data | 2 | **12 - 18** |
| | **Loss of communication link between CCH and FCSs** | FCS (gate) stays at current opening. **Sub-optimal flood protection control.** | 2 - 3 | Interruption of energy supply to sender/receiver on CCH. | 4 | | 4 | **32 - 48** |
| | | | 2 - 3 | Malfunction of sender/receiver on CCH. | 3 | | 4 | **24 - 36** |
| | | | 2 - 3 | Interruption of energy supply to sender/Receiver on FCS. | 4 | CCH does not receive confirmation | 3 | **24 - 36** |
| | | | 2 - 3 | Malfunction of sender/receiver on FCS. | 3 | CCH does not receive confirmation | 3 | **18 - 27** |
| | | | 2 - 3 | Damage to CCH or repeaters due to vandalism, extreme weather, traffic accident. | 3 | | 3 | **18 - 27** |

Table I.2: FMEA of the Centaur system (Gate operation function)

| Name / Function | Potential failure mode | Potential effect(s) of failure | Sev | Potential cause(s) of failure | Occ | Detection Mode | Det | RPN |
|---|---|---|---|---|---|---|---|---|
| B. Gate operation | **Gate stops responding** | **Unable to mitigate flooding.** | 4 | Energy supply interruption (e.g., problem in the network of the energy supplier). | 4* | | 4 | **64** |
| | | **Unable to mitigate flooding.** | 4 | Mechanical problem with the gate. | 3 | CCH detects unresponsive gate. | 2 | **24** |
| | | Flooding in the vicinity of the gate if gate (total or partially) closed because (i) gate is stuck in a pre-set position or (ii) the algorithm has closed it and not opened when the upstream levels become critical. **Potential to cause flooding in the vicinity of gate.** | 4 | Mechanical problem with the gate. But flooding in vicinity unlikely with weir above gate. | 1 | CCH detects unresponsive gate. | 2 | **8** |
| | **Structural failure of gate** | **Potential to cause flooding in the vicinity of gate.** | 4 | Corrosion or plate on which gate attached under-designed. | 1 | | 4 | **16** |

*Likelihood increases during storms