Developing and testing a Fuzzy Logic algorithm to alleviate the risk of flooding by controlling a flow control device in a laboratory setting

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Summary

The aim of the CENTAUR project is to develop a low cost system that is able to mobilise unused distributed storage within sewer networks during rainfall events and so reduce local flood risk. The current system uses a Fuzzy Logic algorithm to regulate a flow control device to reduce the risk of downstream flooding in sewers by maximising the usage of existing upstream storage capacity. This paper presents results from a laboratory study using a full scale pilot system and work undertaken to refine and prove the methodology before implementation in a sewer network.

Keywords

Flow Control, Fuzzy Logic, Urban Flood Risk Reduction, Real Time Control, Urban Drainage.

Introduction

The European Environment Agency has shown that the risk of urban flooding is likely to increase, with the highest risk in the western and northern European states (EEA, 2012). A key factor in many instances of urban flooding is the inability of sewer systems to store or convey a sufficient volume of rainfall run-off, however physical upgrading of the network or the retrofitting of Sustainable Drainage Systems (SuDS) is expensive and/or impractical in many urban areas. The CENTAUR project is aimed at implementing a local Real Time Control (RTC) system to utilise existing storage capacity in the upstream part of a drainage network to reduce the downstream flood risk without the provision of new infrastructure. Implementing an RTC system has been shown to improve the performance of combined sewers by reducing the severity of storm event impacts and is less costly than enlarging the physical capacity of the combined sewers (Ruggaber et al., 2007; Borsanyi et al., 2008).

Ruggaber et al. (2007) utilised real time data from a water level sensor network to control the sewer flow by employing a network of decentralised flow control devices, to utilise the existing storage in the sewer network, and therefore reduce Combined Sewer Overflow (CSO) spill frequencies and volumes. While CENTAUR has some similarities to Ruggaber et al. (2007), the objective function is different in that the objective in Ruggaber et al. (2007) is to control more extreme events (i.e. flooding rather than CSO spills), CENTAUR also utilises fewer and more localised water level monitoring stations and only a single Flow Control Device (FCD) is employed.

The FCD is operated by a Fuzzy Logic (FL) control algorithm informed by local level real time data. Previous work has considered the implementation of Fuzzy Logic for the water industry RTC applications, such as Ostojin et al. (2011) who developed FL for the RTC of Sewer Pumping Stations based on change of level in the wet well. Designing a FL controller requires the development of system rules that interact with the input measured data to produce a decision output. In this case the decision output controls the FCD opening based on water levels measured at locations close to the FCD and the flood location.

The aim of this paper is to present results from laboratory testing of the developed FL control algorithm. Following the laboratory testing, the CENTAUR system has been installed at a pilot site in a live combined sewer network in Coimbra, Portugal.

Methods

This section describes the development of the FL, the layout of the laboratory test facility and also describes the tests carried out.

Fuzzy Logic development

FL control systems are capable of dealing with uncertainties and non-linear systems. FL is a white box model capable of incorporating existing expert knowledge in a form of If-Then rules.

A FL algorithm comprises input and output data, which is linked by a set of rules. Each input and output variable is divided into a series of Membership Functions (MF). Each MF describes a range of data values, and the strength of membership varies between 0 and 1. A particular input value can therefore belong to different degrees to one or more MFs, hence, the term 'fuzzy' which indicates areas that are partially true and false. Rules are designed based on expert knowledge to link the input data to an output MF. For example, the human reasoning used when crossing a road is analogous to a FL algorithm, the input variables could include road width, speed of traffic and how far away the traffic is. The output MFs would describe whether to cross the road and how fast (e.g. Don't Cross, Run, Walk). Rules for this example might include 'If the Road is Narrow, the Traffic is Far Away and Travelling Fast Then Walk across the road'. The algorithm then processes the results of all rules to give the output result (defuzzification). In CENTAUR the input data is based on collected water levels and the output describes whether the FCD opening should be adjusted and hence the flow of water through the FCD is changed which would increase or decrease the amount of water stored upstream. Fig. 1 gives an example of the output membership functions for FCD opening. It can be seen that there are overlaps between different membership functions, so for a given input value more than one membership function might apply to a certain degree.

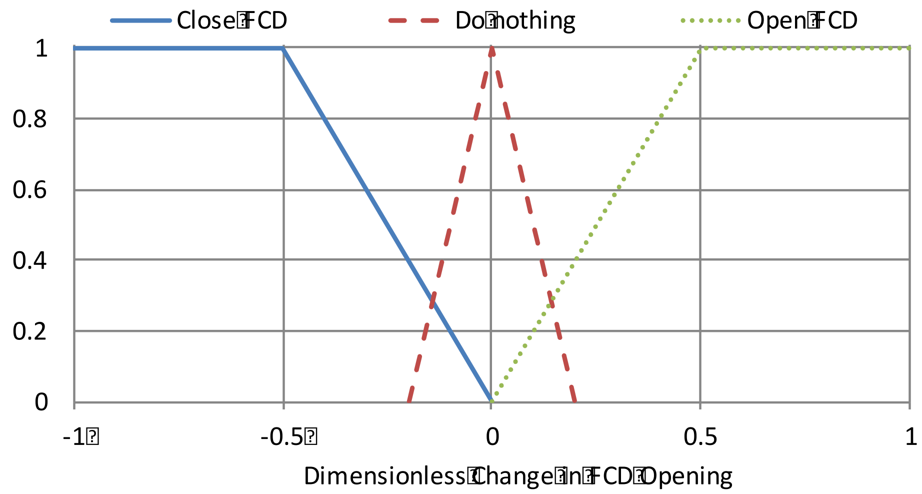

Fig. 1. *Membership function example of an FCD opening.*

The Fuzzy Logic rules and membership functions for CENTAUR have been developed based on expert knowledge with initial virtual testing in a SWMM hydrodynamic model linked to Matlab, as described in Shepherd et al. (2016). This project is funded under an H2020 Innovation Action and has a commercial element, hence it is not possible to provide full details of the FL control algorithm developed for CENTAUR.

Laboratory test facility

The laboratory facility, shown in Fig. 2, has been constructed specifically to test the CENTAUR system. The facility is designed to be effectively full scale, it consists of a 30 m long “sewer” pipe, 0.2 m in diameter with four, 1.5 m high and 1 m in diameter, manholes. The manholes are labelled MH1 to MH4, where MH1 is the upstream manhole. Water is fed into the system via a pair of submersible pumps capable of a combined output flow of 50 l/s, with the flow rate controlled by upstream butterfly valves after each pump. A further butterfly valve, at the downstream end of the 0.2 m diameter “sewer” pipe controls the water level and hence replicates backwater effects. The flow control device (FCD), installed in the third manhole (MH3), has a 0.2 m diameter and has been supplied by Steinhardt. The gradient of the pipe profile along the rig is 1 in 500. The facility includes two level monitoring sites (LMS), these are in MH3 (upstream of the FCD) and in MH4, which represents the potential flood location. Each LMS has a single pressure transducer which measures water level data at 0.1 Hz, the water level is reported relative the manhole invert level.

The FL control algorithm is hosted on the ‘Communication and Control Hub’ (CCH) which is a simple rugged linux PC. Data from the LMS are transferred wirelessly to the CCH via repeaters, the CCH processes the data and runs the FL control algorithm every 60 seconds. If a control action is required the CCH sends the command via a repeater to the FCD.

The laboratory system is controlled using National Instruments LabView software, this is designed to control the inflow valves and also the downstream valve. Both sets of valves can either be set at a fixed value, or a time series can be programmed.

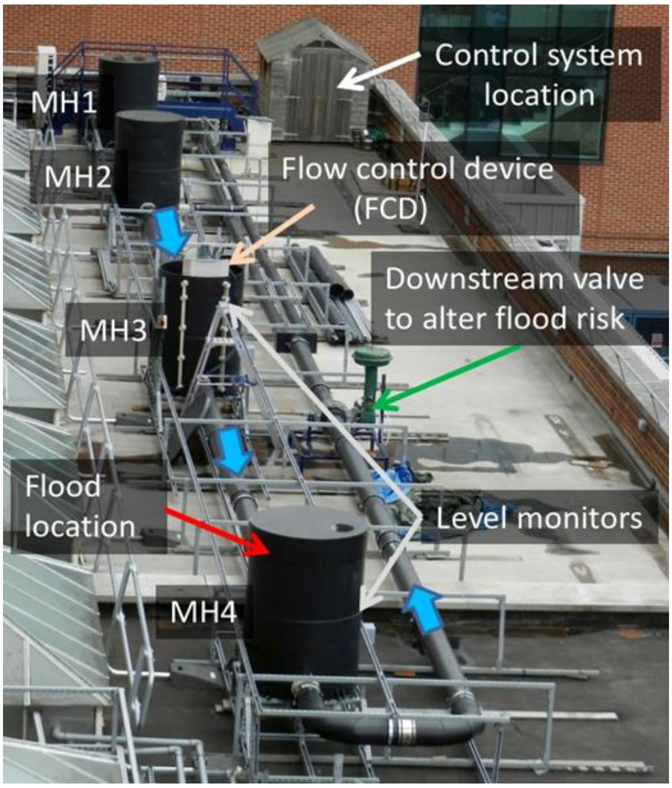

Fig. 2. *Laboratory facility designed to test the CENTAUR system.*

Laboratory testing

The laboratory testing programme aims to test the CENTAUR system including both the hardware and software to ensure the system is reliable and produces the expected control. The tests also examine the repeatability of the FL control actions. The design of the test facility means that the 'flood location' does not actually flood, but instead a target water level (50 cm) is used to represent the level at which flooding would occur. The initial testing has used a constant rate of inflow, with water levels controlled by the downstream valve to represent the variation during a rainfall event. In this paper, results from a single flow rate of 6.5 l/s are presented, at this flow rate all pipes run un-surcharged when the downstream valve is fully open.

As noted earlier, initial rules and MFs have been developed in a 'virtual' testing environment using hydrodynamic models. During the laboratory testing, the MF parameters and rules have been adjusted to better understand the performance and sensitivity of the control algorithm. Thus far, over 170 tests have been carried out at a range of steady flow rates with different downstream valve profiles, testing different parameters in the FL algorithm and understanding the repeatability of the control actions. Results from a small selection of tests, which can show the performance of the system and refinement of the control algorithm, are presented. These tests are: a baseline or control case where the FCD is fully open and the FL control algorithm is inactive (Test 1); an initial test using the control algorithm developed in the virtual testing environment with only key drainage system parameters changed (e.g. water level at which flooding occurs) (Test 2); a refined version of the control algorithm which was repeated 3 times to investigate the repeatability of the system (Tests 3 to 5). These tests are listed in Tab. 1.

Tab. 1. *List of laboratory tests.*

Test	Fuzzy Logic used	Description
1	None	Baseline scenario. FCD fully open and FL control algorithm inactive.
2	Initial	An example of implementing an early stage of FL code development.
3	Refined version	Refined based on expert knowledge and results of laboratory tests.
4	Refined version	To investigate repeatability.
5	Refined version	To investigate repeatability.

Results and Discussion

This section presents results of the tests described in Tab. 1. Fig. 3 shows the baseline test and includes plots of water levels and the downstream valve opening profile which was designed to replicate the change in water levels due to runoff from a storm event passing through the sewer system. The water levels plotted in Fig. 3, can be seen to follow a similar pattern at both the flood location and upstream of the FCD. Prior to the rainfall event, the water level upstream of the FCD (MH3) was around one third of that at the flood location (MH4) before the start of downstream valve closure. The difference in water levels is primarily due to the backwater effects of two sharp bends immediately downstream of MH4.

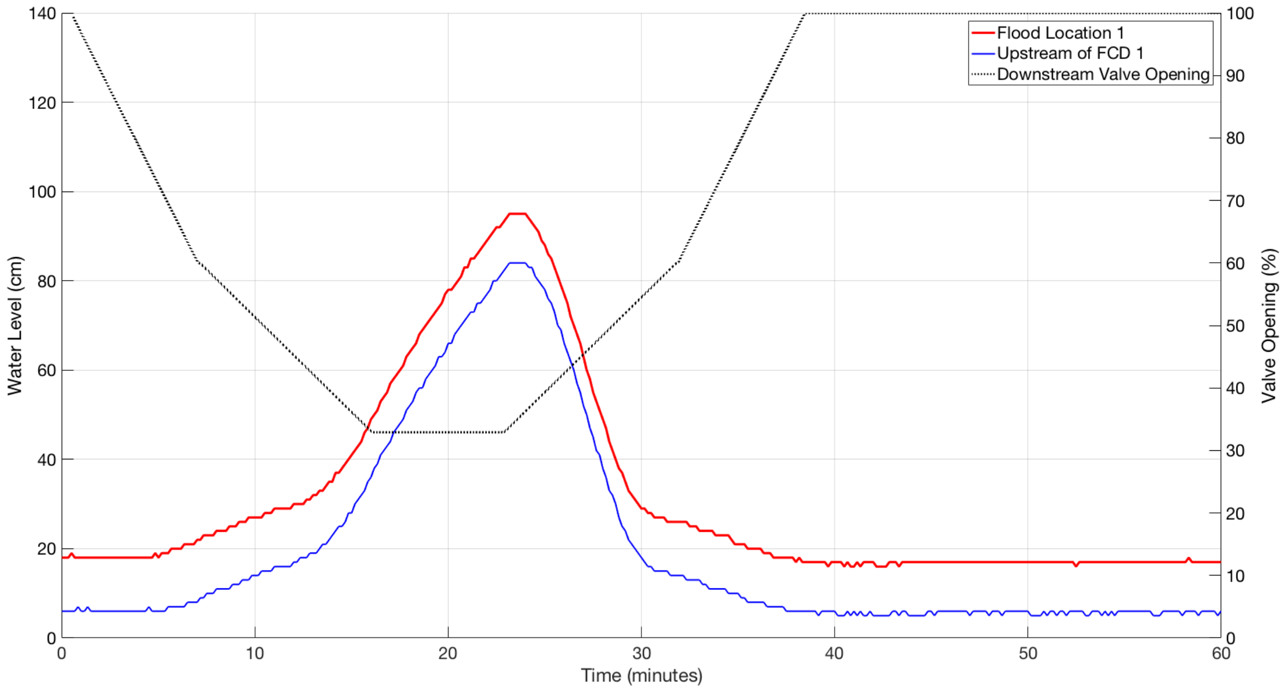

Fig. 3. *Water levels for Test 1 where the FCD was inactive (baseline scenario).*

Fig. 4 shows the results of Tests 2 and 3 where the FCD is being operated by the FL algorithm. A flood level of 50 cm at the flood location is used as the control parameter, so the target to minimise flooding is achieved by reducing the maximum water level to 50 cm or less, in the baseline case (Fig. 3) this level is breached for 12 minutes. The water levels presented in Fig. 4 (red and blue lines) are relative to the baseline case (i.e. the baseline water level is subtracted from the water level recorded for the tests presented) and hence the levels plotted are showing the effect of the CENTAUR system. The opening of the FCD is also presented (black lines), where 20 cm is fully open. Towards the end of the event, once water levels drop below a pre-defined threshold (set to 20 cm in these tests), the FCD is re-set to the fully open position.

Referring to Fig. 4, Test 2 which is the initial control algorithm (dashed lines), results in a maximum water level reduction of 19 cm, while the water level upstream of the FCD is approximately 30 cm higher showing significant amounts of stored water. The minimum FCD closure in Test 2 was 4 cm. It can however be seen that by comparing the timing of the maximum flood reduction (around 28 minutes in Test 2) that this occurs after the peak of the flooding (around 23 minutes in baseline), hence the benefit of the CENTAUR system is not optimised, storage needs to be utilised earlier. Comparing absolute water levels (not shown for Test 2), the initial control algorithm has resulted in a decrease in the flooding duration of 2 minutes to 10 minutes with the peak level reduced by 7 cm to 88 cm.

Following the refinement of the FL algorithm by adjusting the MFs, Test 3 in Fig. 4 (solid lines) can be seen to improve the control of the FCD, with the initial closure being 6 minutes earlier and the minimum opening being 1.2 cm. The refined control algorithm has resulted in a maximum flood reduction of 54 cm compared to the baseline and this occurs close to the peak of the baseline flooding. The peak water level in Test 3 is reduced by 33 cm to 62 cm and the time spent above 50 cm is reduced by a further 6.5 minutes to 3.5 minutes (this data can be seen in Fig. 5). Fig. 4 shows that the FCD remains partially closed for a longer period in Test 3, this is because the stored water is gradually released after the storm event and Test 3 stored significantly more water upstream of the FCD, as evidenced by the peak water level of 128 cm (Fig. 5).

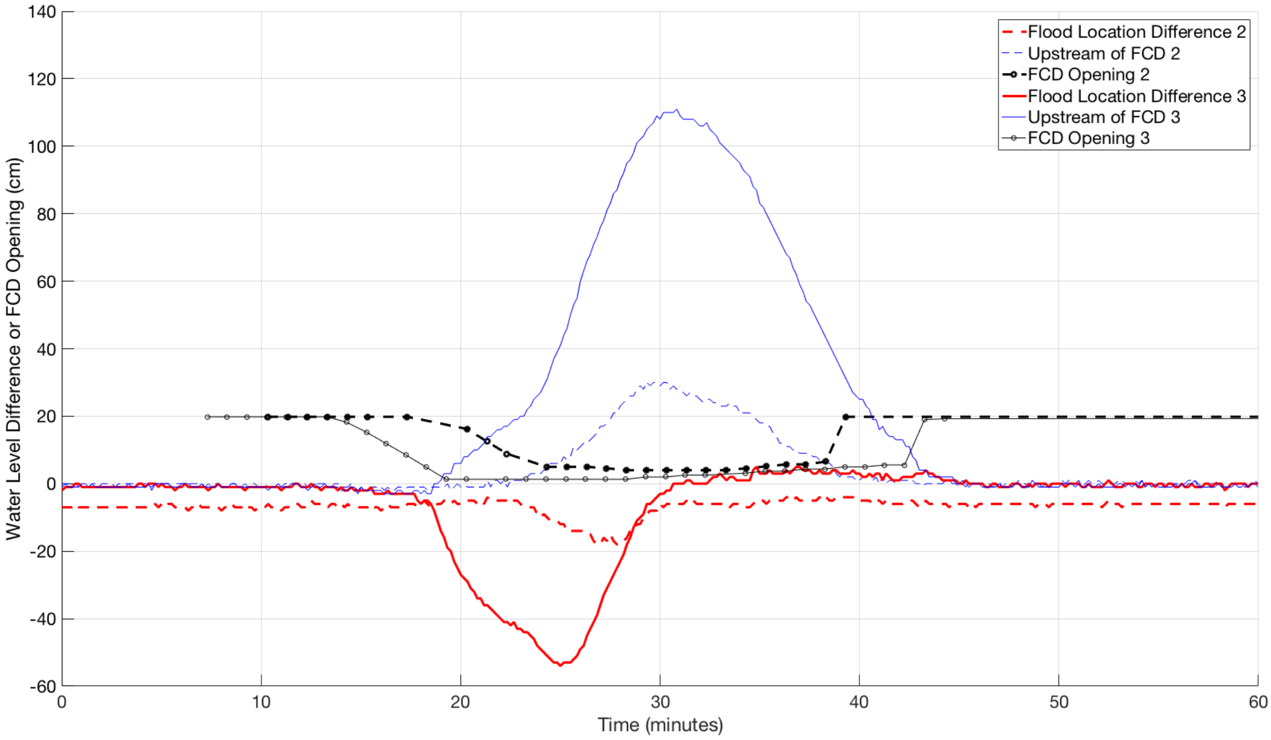

Fig. 4. *Effect of the CENTAUR system on water levels and FCD opening for Tests 2 and 3.*

The repeatability of the CENTAUR system was investigated in Tests 3, 4 and 5, for which all settings, including the control algorithm, flow rate and downstream valve profile are identical. Fig. 5 shows good repeatability, especially in the early part of the storm event where the water levels and FCD opening are very similar across all three tests. In the latter part of the storm event, Test 3 (solid line) showed slightly different results to Tests 4 and 5, the water level upstream of the FCD drops more rapidly and the FCD reaching the fully open state four minutes earlier than that of Tests 4 & 5. Further analysis shows that this is most likely due to the whole re-opening phase being slightly faster, resulting in a higher flow through the FCD and more rapid drop in the level of the stored water. This more rapid re-opening is due to small differences in the measured water levels affecting the FL MFs and hence triggering a stronger opening command to the FCD.

The testing carried out using the laboratory facility has allowed development of the CENTAUR system, improved understanding of the FL control algorithm parameters and proven the reliability and repeatability of the system to a point where the project team are confident to deploy the system in Coimbra. Further work is still planned in the laboratory facility to investigate a wider range of event profiles, including multi-peaked events. It is also planned to vary the inflow to the facility instead of, or in addition to adjusting the downstream valve to further increase the number and type of events tested. Parallel work investigating the optimisation of the FL parameters using a Genetic Algorithm and a hydrodynamic model is also ongoing.

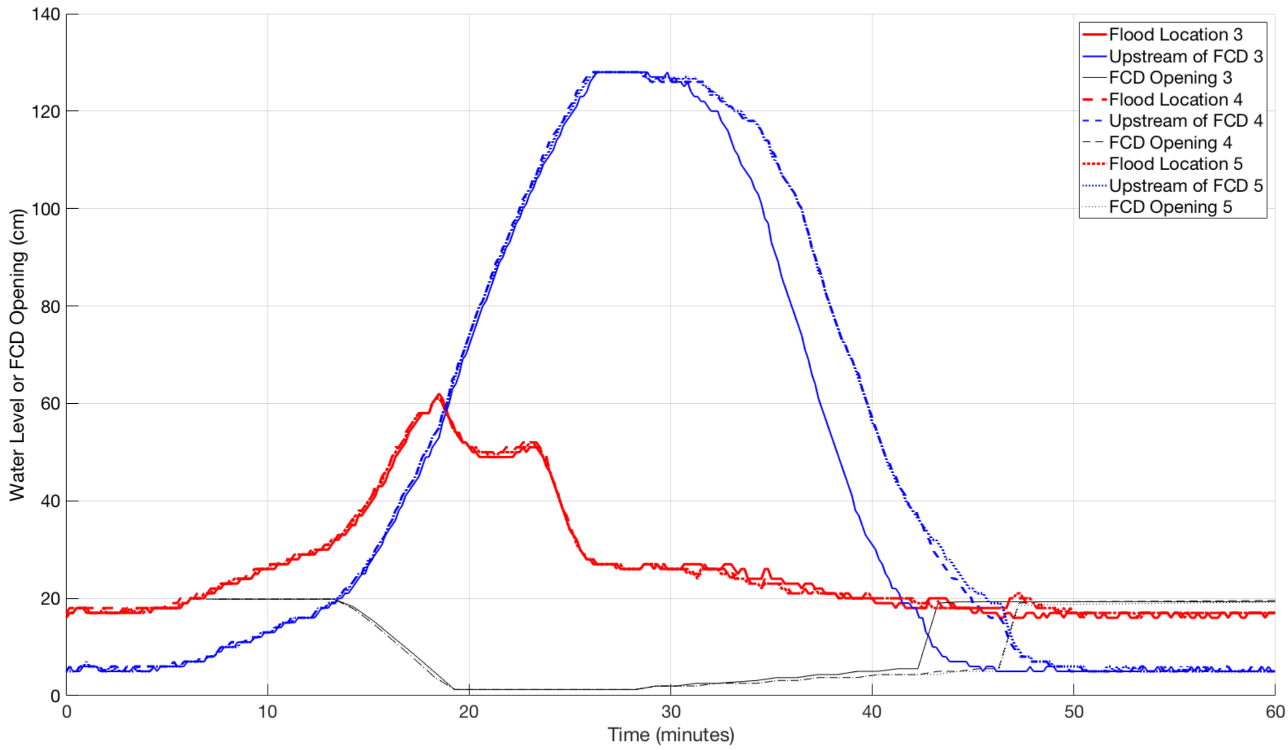

Fig. 5. *Repeatability of the CENTAUR system - Tests 3, 4 and 5.*

Conclusions

- The CENTAUR system has been tested in a full scale laboratory facility.
- CENTAUR has been shown to significantly reduce flooding, both in terms of levels and duration. The duration above the 50 cm flood level for the presented pseudo-rainfall event was reduced from 12 to 3.5 minutes and the peak level reduced by 33 cm.
- The system has been shown to give good repeatability, results from 3 tests demonstrated that the FCD closed almost identically and only showed small explainable differences in re-opening.

Acknowledgments

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