First Flush Rainwater Harvesting Application with Fuzzy Logic Control

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Abstract- **Industrial pollution in urban areas, fossil fuels from vehicles and buildings can result in rainwater pollution. Additionally, dust, solids, and fecal deposits from birds and rodents, which accumulate on rooftops during dry periods, may also affect the quality of harvested rainwater. Therefore, the first-flush of the roof runoff water; i.e. the first water volume of the rainfall event, may contain pollutants at increased concentrations. This paper presents a roof rainwater harvesting system, which uses fuzzy logic control to convert the direction of the runoff water, between two tanks, which collect, filter and then forward the water for reuse. The purpose is to separate the first flush rainwater from the remainder, i.e. the black from the grey water respectively. The presented system is a part from a larger open source autonomous water-waste management system which was installed on a building located at an urban area of Crete in southern Greece.**

Key words- First flush, fuzzy control, harvesting system, urban wastewater management system, IoT.

I. INTRODUCTION

The availability of fresh water is a major issue which greatly affects the population growth in an area. This is directly attached to a number of factors such as urbanization, land use transformation, pollution and climate patterns changing [1]. Many solutions have been proposed, with much interest in the use of roof-collected rainwater. Rainwater harvesting is an ecological and tolerable method of water management, resulting in the reduction of urban runoff and flooding, and of course water saving [2]. Using rainwater for various human needs retrenches the fresh water that would be used for fulfilling the same needs if not recycling it.

The roof runoff quality is affected by rainwater quality and, roof and/or building features (e.g., length, material, location). Industrial pollution in urban areas, fossil fuels from vehicles and buildings, and/or agricultural activities (pesticides emission) in nearby rural areas can result in rainwater pollution [3]. Additionally, dust, solids, and fecal deposits from birds and rodents, which accumulate on rooftops during dry periods, may also affect the quality of harvested rainwater [4]. Therefore, the first-flush of the roof runoff water; i.e. the first water volume of the rainfall event, may contain pollutants at increased concentrations. An improved quality of the harvested water can be achieved by installing a device (or in this case a valve) which will separate the first-flush water, from the remainder water collection [5].

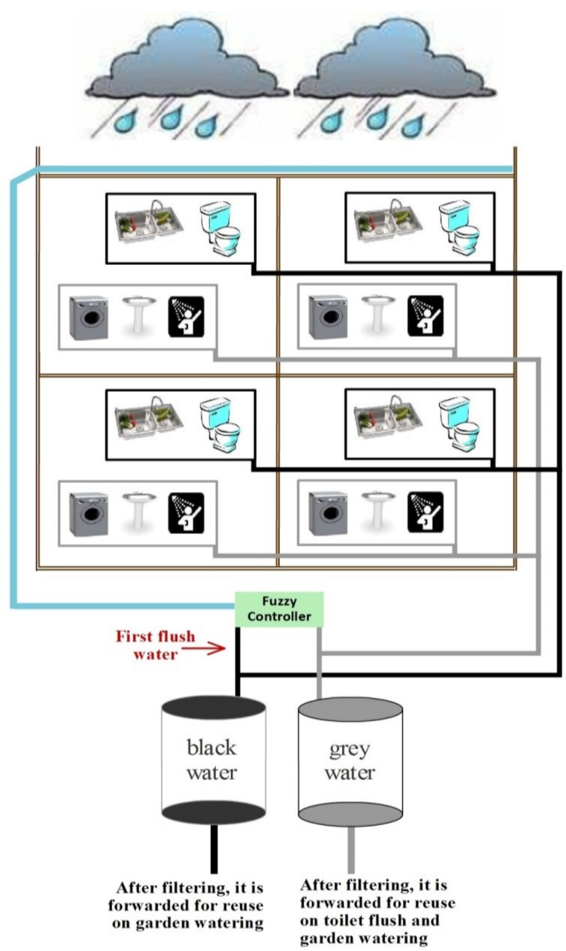

Fig. 1. Waste-water harvesting system

This paper presents a roof rainfall harvesting system, which uses fuzzy logic control to convert the direction of the runoff water, between two tanks. The purpose is to separate the first flush rainwater from the remainder, so that can be treated as black and grey water respectively. The presented system is a part from a novel IoT system, named HOLISTIC, that monitors, controls and manages the residential water infrastructure, which was installed in a block of flats located at an urban area of Crete in southern Greece. This system collects wasted water from the building (apartments and outdoor surfaces), divides it into two tanks (grey and black), filters and processes it and drives it for reuse at a roof garden for irrigation and at toilet flushes. All the system's modules use open source software and hardware technologies. The remainder of the paper is organized as follows: section II introduces to the various uses of Fuzzy Logic Control, section III presents the First Flush concept of the HOLISTIC framework, section IV analyzes the development of the HOLISTIC's Fuzzy Logic controller and finally, section V concludes the paper.

II. FUZZY LOGIC AND APPLICATIONS

The logic applied to a controller in order to manage a system or a process, can vary from simple binary conditions, to mathematical expressions, or even complex algorithms such as fuzzy reasoning [6]. In the present paper a fuzzy logic controller was selected and implemented for a first flush system.

Fuzzy reasoning is a powerful and straightforward means of problem solving, which is designed on the basis of human experience [7] and provides a controller without the requirement of a mathematical model [8]. An important problem with first flush method is the need to cope with the large amount of uncertainty, which is inherent of natural environments. Fuzzy logic's features make it a suitable tool to address this problem [9].

Fuzzy logic (FL) has emerged as an important part of expert system which has proved to provide solution to real life problems [10]. It has been successfully applied in a variety of fields ranging from engineering, to financial sector, from medicine, to agriculture and many more, for over twenty years.

Saffiotti in [9] reviews some of the possible uses of fuzzy logic in the field of autonomous navigation in real-world environments. He focuses on four issues: how to design behavior-producing modules; how to coordinate the activity of several such modules; how to use the sensors' data; and how to integrate low-level execution with high-level reasoning.

Fuzzy logic approaches for traffic signal control were reviewed in [11]. The results of these applications indicate better performance than traditional traffic signal controls, especially during heavy volume and uneven traffic conditions.

An automatic analysis of X-ray images was performed in [12] using fuzzy logic techniques, for the inspection process of industrial manufacturing systems. The fuzzy reasoning was applied to decide whether the object, displayed on the image, was defected or not.

For forecasting exchange rates, a predictive model with the use of fuzzy logic theory was created in [13]. To evaluate its effectiveness it was then tested with data from times of prosperity and during financial crisis, with high efficiency rates.

In [14] the authors introduce type-2 fuzzy sets in intelligent trading algorithms, in order to improve the risk-adjusted performance with the minimum increase of the design and computational complexity.

Hybrid systems, which integrate both the management of uncertainty and inherent interpret-ability of fuzzy rule based systems, with the learning and adaptation capacity of evolutionary optimization, have become popular in the last years. A review of the progression of evolutionary fuzzy systems has been done in [15], analyzing their taxonomy and components.

A fuzzy c-means clustering algorithm was implemented in [16] to find subgroups of patients, and then develop a fuzzy model for each subgroup to achieve personalized healthcare for individual patients of ICU, fitted to the individual rather than the "average" patient.

A study of fuzzy logic integrations with expert systems which has been applied in the field of agricultural sciences is presented in [10] along with a review of a few of applications.

III. HOLISTIC's FIRST FLUSH CONCEPT

In a block of flats located at an urban area of Crete in southern Greece, a novel Internet of Things (IoT) system, called Holistic, has been installed. This system monitors, controls and manages the residential water infrastructure. It collects all water-waste from the four apartments located at the building, and from the outdoor surface (roof). The waste-water is dividing into two separate and airtight tanks based its source (grey or black, for more details see Fig.1). After the harvest, the grey and black water gets filtered and then promoted for reuse on garden watering and on toilet flush.

The control code developed for Holistic system was divided to different modules in order to manage all the different tasks. In this paper we focus on the module created for the roof runoff, which includes the concept of the first-flush on an outdoor surface and the intelligence of fuzzy logic to control it.

For improving the quality of the roof harvested water, a solenoid valve has been installed at the runoff tube drainage and controlled with fuzzy logic to separate the first-flush water; i.e. the first water volume of the rainfall event (containing pollutants at increased concentrations), from the remainder harvest water. Considering the surface features (length, material, location - near highway) and some extended experimental data, we reached to a model which will receives two input variables, the rainfall intensity and the drought duration, and produces the time after which the first flush event must end.

The first input of the fuzzy controller is the rainfall intensity which is given in millimeters per hour (mm/h) in real time from a weather station located at the building. The second input is a bit more complex. In the Mediterranean area where the building is located, the duration between two rain events may vary from five minutes to three months. As a result we cannot accept as dry period the time interval between two rain events. This could result to a wrong calculation of the first flush time. Considering this fact and the cement base of the roof surface, as drought duration we calculate the time passed between a “clean” roof surface; i.e. when the valve changed status as an indication of a completed first flush event, and the new rain event.

When a rain event starts, the fuzzy controller receives the values of these two inputs (rainfall intensity and drought duration) and returns a time value (in minutes - output) in which the current first flush event needs to be concluded.

For the design and analysis of the fuzzy controller we used Matlab/Simulink. The same principles were then applied in java code, using the open source Java library jFuzzyLogic [17], in order to implement the FLC to the larger waterwaste management system of the building.

IV. FUZZY LOGIC CONTROLLER (FLC)

The first flush concept described in this paper has been implemented using a Mamdani fuzzy logic controller. A fuzzy logic controller relates the output to the inputs using rules; i.e. a list with IF-AND/OR-THEN statements. The IF-AND/OR-part of the rules refers to the linguistic names of certain regions (fuzzy sets) of the input variables. Each input value belongs to these regions represented by a certain degree of membership [18]. The logical AND has been implemented with the minimum operator, and the THEN-part of the rules refers to values of the output variable. To acquire the output of the FLC, the degrees of membership of the IF-AND/OR-parts of all rules are evaluated, and the THEN-parts of all rules are calculated by the geometric center of the area (or center of gravity), under the membership functions and within the range of the output variable. Figure 2 presents the structure of some of the rules used in this FLC. Figure 3 illustrates an example of the calculation of the center of the gravity used for two rules WITH different weights (i.e. the last two rules on Fig.2).

```
IF  drought IS week1  AND  rainFall IS I75  THEN  valveTime IS delay0  WITH 1;
IF  drought IS week1  AND  rainFall IS I115 THEN  valveTime IS delay0  WITH 1;
IF  drought IS week1  AND  rainFall IS I55  THEN  valveTime IS delay2  WITH 1;
IF  drought IS week1  AND  rainFall IS I15  THEN  valveTime IS delay8  WITH 1;
IF  drought IS week1  AND  rainFall IS I15  THEN  valveTime IS delay12 WITH 0.2;
IF  drought IS week2  AND  rainFall IS I15  THEN  valveTime IS delay8  WITH 1;

IF  drought IS week2  AND  rainFall IS I95  THEN  valveTime IS delay0  WITH 1;
IF  drought IS week2  AND  rainFall IS I95  THEN  valveTime IS delay2  WITH 0.6;
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Fig. 2 Rules

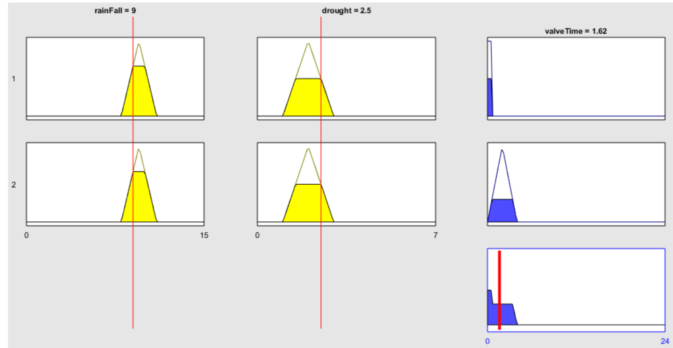

Fig. 3 Center of gravity

Table I shows the general setting made to the fuzzy logic controller, as well as the membership factions’ names and parameters.

TABLE I
General Setting for the Fuzzy Controller

Variable	Name	Range	Number of membership functions
Input	rainFall	[0 15]	9
	drought	[0 7]	6
Output	valveTime	[0 24]	13
Defuzzification method:			Centre of area
Antecedent connective:			And (Minimum)
Implication:			Minimum
Minimum Degree of support:			1.00

It is worth noting that the shape and number of the membership functions of each fuzzy set, as well as the inference mechanism of the fuzzy logic, was selected based on trial-and-error methods, in a way that the region of interest of the input data is covered appropriately. The selected shapes of the membership functions, associated to the FLC linguistic variables, are piece-wise linear functions (triangular or/and trapezoidal). Tables II, III and IV contain the analytic settings of each membership function and its fuzzy sets, and figures 3, 4 and 5 present the graphical representation of these functions.

TABLE II
Input membership function rainFall

Membership function	**Shape**	**Points**
I08	trapezoid	0 ; 0 ; 0.5 ; 1.2
I15	triangle	0 ; 1.5 ; 3
I35	triangle	2 ; 3.5 ; 5
I55	triangle	4 ; 5.5 ; 7
I75	triangle	6 ; 7.5 ; 9
I95	triangle	8 ; 9.5 ; 11
I115	triangle	10 ; 11.5 ; 13
I135	triangle	12 ; 13.5 ; 15
I140	trapezoid	14 ; 15 ; 15 ; 15

TABLE III
Input membership function drought

Membership function	Shape	Points
week1	trapezoid	0 ; 0 ; 1 ; 2
week2	triangle	1 ; 2 ; 3
week3	triangle	2 ; 3 ; 4
week4	triangle	3 ; 4 ; 5
week5	triangle	4 ; 5 ; 6
week6	trapezoid	5 ; 6 ; 7 ; 7

TABLE IV
Output membership function valveTime

Membership function	Shape	Points
delay0	trapezoid	0 ; 0 ; 0.5 ; 0.7
delay2	triangle	0 ; 2 ; 4
delay4	triangle	2 ; 4 ; 6
delay6	triangle	4 ; 6 ; 8
delay8	triangle	6 ; 8 ; 10
delay10	triangle	8 ; 10 ; 12
delay12	triangle	10 ; 12 ; 14
delay14	triangle	12 ; 14 ; 16
delay16	triangle	14 ; 16 ; 18
delay18	triangle	16 ; 18 ; 20
delay20	triangle	18 ; 20 ; 22
delay22	trapezoid	20 ; 22 ; 24 ; 24
delay24	trapezoid	24 ; 24 ; 24 ; 24

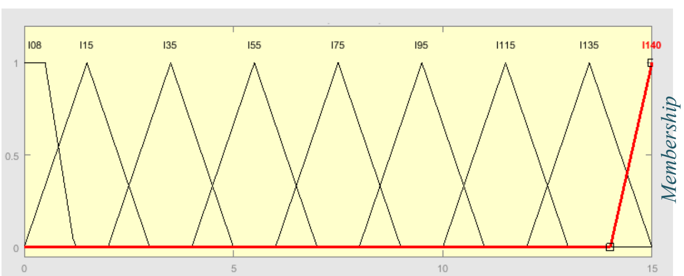

Fig.4. Input membership function rainFall

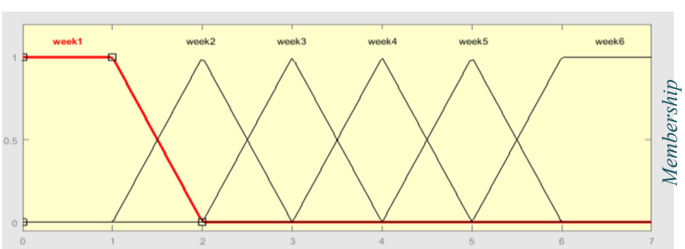

Fig.5. Input membership function drought

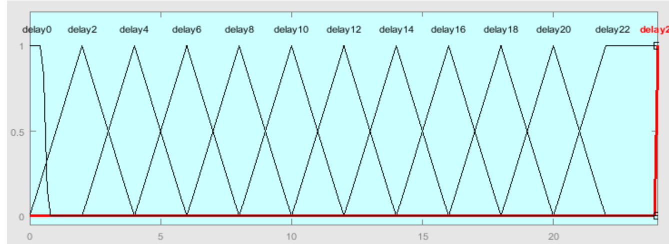

Fig.6. Output membership function valveTime

Figure 7 illustrates the control surface of the fuzzy logic controller. In more detail, it shows the connection between the inputs (rainFall and drought) and the output (valveTime) that derives from the base of knowledge, i.e. the rules used for this FLC. The vertical contour of the plot indicates the value of the output variable, and the two horizontal the values of the two inputs. This surface helps developers to understand the behavior of the controller [19].

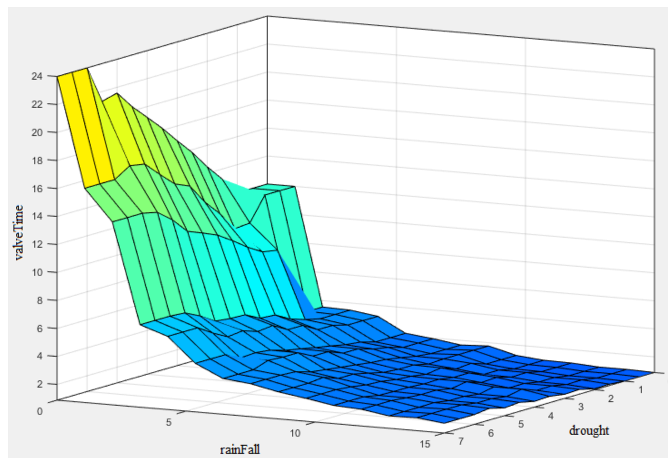

Fig.7. Control surface based on the rules

The fuzzy controller as a part of the larger Holistic system it is initiated when a condition is true; in this case when rain has started. When the rain sensor receives indication of rain (rain intensity), the main system, calculates the drought time and initializes the fuzzy controller with these two inputs.

When the FLC returns the time value (output), the system changes the valve's status, forwarding the first flush runoff towards the black water tank and starts a countdown. When the time passes (i.e. the first flush ends), it changes the valve status towards the grey tank. Every one of these events is registered to a log file. Figure 8 shows one full cycle of a rain event as well as the output of the FLC, when the rain intensity is 5mm/h and the drought duration is 10days (output time is 6min).

id	event	apId	value	eventStart	eventStop
52129	rainStart	0	5	2016-01-18 10:32:12	2016-01-18 10:32:12
52130	ffFunctionCallResponse	0	6.0	2016-01-18 10:32:12	2016-01-18 10:32:13
52131	ffSetValveToBlack	0	0	2016-01-18 10:32:13	2016-01-18 10:32:13
52132	ffSetValveToGrey	0	1	2016-01-18 10:38:13	2016-01-18 10:38:13
52133	rainStopped	0	0	2016-01-18 11:30:45	2016-01-18 11:30:45
52134	ffSetValveToBlack	0	0	2016-01-18 11:30:45	2016-01-18 11:30:45

Fig.8. Log file – A full cycle run for a rain event

V. CONCLUSION

In this paper, a fuzzy-logic-based controller for handling the first flush event of a rain runoff has been presented. This controller calculates the time needed to consider the first flush event ended; i.e. the pollutants have been washed out of the surface of the roof, and the valve can change status to drive the remainder runoff to a different concentration tank. Fuzzy logic is an intelligent, cost-effective and nonlinear control, capable of encountering the uncertainty which is inherent of natural environments, therefore a suitable tool to address a first flush harvesting problem.

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