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Developing a fuzzy logic based system for monitoring and early detection of residential fire based on thermistor sensors

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Abstract. The recent proliferation of global networking has an enormous impact on the cooperation of smart elements, of arbitrary kind and purpose that can be located anywhere and interact with each other according to the predefined protocol. Furthermore, these elements have to be intelligently orchestrated in order to support distributed sensing and/or monitoring/control of real world phenomena. That is why the Internet of Things (IoT) concept raises like a new, promising paradigm for Future Internet development. Considering that Wireless Sensor Networks (WSNs) are envisioned as integral part of arbitrary IoTs, and the potentially huge number of cooperating IoTs that are usually used in the real world phenomena monitoring and management, the reliability of individual sensor nodes and the overall network performance monitoring and improvement are definitely challenging issues. One of the most interesting real world phenomena that can be monitored by WSN is indoor or outdoor fire. The incorporation of soft computing technologies, like fuzzy logic, in sensor nodes has to be investigated in order to gain the manageable network performance monitoring/control and the maximal extension of components life cycle. Many aspects, such as routes, channel access, locating, energy efficiency, coverage, network capacity, data aggregation and Quality of Services (QoS) have been explored extensively. In this article two fuzzy logic approaches, with temporal characteristics, are proposed for monitoring and determining confidence of fire in order to optimize and reduce the number of rules that have to be checked to make the correct decisions. We assume that this reduction may lower sensor activities without relevant impact on quality of operation and extend battery life directly contributing the efficiency, robustness and cost effectiveness of sensing network. In order to get a real time verification of proposed approaches a prototype Sensor web node, based on Representational State Transfer (RESTful) services, is created as an infrastructure that supports fast critical event signaling and remote access to sensor data via the Internet.

Keywords: fire protection, fuzzy logic, representational state transfer, sensor web, temperature sensor, wireless sensor networks.

1. Introduction

With the threats, risks and dangers that exist today, fire and particularly fire security systems play an increasingly significant role in life-safety operations. Fire can cause massive damage to the indoor or outdoor area, creating the severe life threatening conditions, making the early and accurate residential fire detection extremely important for prompt extinguishing, reducing the damages and potential life losses. The integration of fire-safety systems within building automation infrastructure, through fast delivery of sensed data, quick response, access control, video surveillance, fire detection and alarm, and emergency communications aides the effective incident management.

One of the ways to monitor and detect fire is to use the Wireless Sensor Networks (WSN) composed of low-resourced sensor nodes. WSNs are designed and deployed for different purposes by various organizations. They are composed of spatially distributed nodes equipped with sensing devices (to monitor environmental conditions at different location), processing unit, communication components (wireless transmitter/receiver), storage unit, and an energy source (power unit) (Fig. 1).

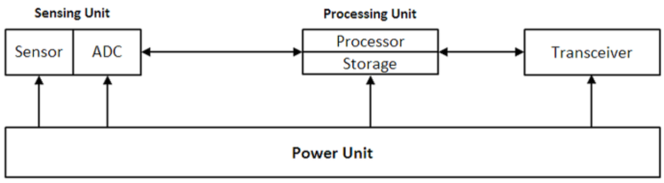

Fig. 1. Typical architecture of a sensor node

These tiny sensing devices have limited possessing and computation capabilities, and can collaborate in: real-time monitoring; sensing; collecting network distribution of the various environments within the region; or monitoring object information [1]. Nodes communicate with their neighbors and forward data to the sink through multi-hop routes. The observations obtained from sensor networks may be helpful in many software applications like industrial monitoring, building and home automation, medicine, environmental monitoring, urban sensor networks and intelligent transportation. These networks can also be used for security purposes, military defense, disaster monitoring and prevention, etc. [2] Many aspects, such as: routes; channel access; locating; energy efficiency; coverage; network capacity; data aggregation; and Quality of Services (QoS) have been explored extensively. Nowadays, problems studies of practical WSN applications, rather than theoretical researches, have become a topic of great interest [3]. Event detection is one of the main components in numerous WSN applications. To detect critical events like fire, one or a combination of sensors and detection algorithm is needed. The sensors might be part of a WSN or work independently [4]. Thus, the detection of a critical event should be delivered to the user as soon as possible.

Recent advances in WSN technology and the use of the Internet Protocol (IP) in resource constrained devices has radically changed the Internet landscape creating a new form called Internet of Things (IoT) [5]. The IoT will connect physical (analog) environments to the (digital) Internet, unleashing exciting possibilities and challenges for a variety of application domains, such as smart metering, e-health logistics, building and home automation [6].

In order to show how the WSN based system for continuous monitoring and/or recording critical temperature values, powered by fuzzy logic detection mechanism and web enablement, can be designed and deploy, the rest of the paper is organized as follows. Section 2 presents the related work analysis. In Section 3 the use of fuzzy logic in WSNs for fire detection, through two proposed approaches together with the highlighted assumptions and goals of the research, is presented. Section 4 presents: the process of Sensor Web structure creation; proposed fuzzy approaches testing based on two different temperature sensors application; and the way of data processing and visualization. Section 5 describes the obtained measurement results while Section 6 provides conclusion remarks and outlines the directions for future work.

2. Related work

The WSNs are typically used to monitor some of the parameters of environmental processes which are complex, ambiguous and vagueness embedded in their nature. Most previously performed researches in WSNs rely on precise, also called crisp, values to specify the parameters of interest. As the consequence of such a rigid approach, the sensor readings can be imprecise and unreliable, making the using of crisp values to describe WSN parameters inadequate. In spite of the fact that sensor nodes have highly constrained resources (microcontroller, memory, battery, communications), numerous new functionalities have been proposed for WSNs. Considering that WSNs are envisioned as an integral part of the Future Internet, supporting its extension to the physical world, the incorporation of soft computing (SC) technologies in sensor nodes may lead to potential network performance improvements, since it provides effective parameter combination and can be directly executed by the sensor nodes. Integration of soft computing technologies (fuzzy logic, neural networks, fuzzy rule-based systems, data mining techniques, etc.) in sensor nodes is a good example of an application adapted to WSNs [7]. Authors of [8] believe that crisp values cannot adequately handle the often imprecise sensor readings and that is why they propose fuzzy values instead of crisp ones claiming that they significantly improve the accuracy of event detection. Therefore, WSN powered by a fuzzy logic detection mechanism, behaves like intelligent and power efficient sensing network.

The incorporation of fuzzy logic or fuzzy approach in WSNs is presented in numerous papers. Fuzzy logic provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input data/information [9]. What makes fuzzy logic suitable for use in WSNs is that: it can tolerate unreliable and imprecise sensor readings; it is much closer to the human way of thinking than crisp logic; and it is much more intuitive and easier to use, when compared to other classification algorithms based on the probability theory. In WSNs, fuzzy logic has been generally used to improve the decision-making process, reduce resource consumption, and increase performance. A main disadvantage of using fuzzy logic is that the number of rules grows exponentially to the number of variables (with n variables, each of which can take m values, the number of rules in the rule-base is m^n) demanding a significant amount of memory for storing the rule-base [8]. To solve this problem, efficient rule-base reduction techniques, with different advantages and modeling needs, are developed. A key property of these techniques is that they do not affect the application accuracy. Some of the rule-base size reduction techniques are described in [10-13].

In [8, 11] authors present a method of fire detection based on fuzzy logic. They used the temperature, temperature change, smoke obscuration and smoke obscuration change as input variables with three level values: low, moderate, and high. Fire confidence is defined as the output of fuzzy logic system. The experiment has shown that fuzzy logic is a powerful and accurate mechanism which can be successfully applied to the event detection in WSNs. Compared to the crisp values approach, fuzzy logic allows the detection algorithm to maintain a high accuracy level despite fluctuations in the values acquired from sensor. This helps decreasing the number of false positives while still providing fast and accurate event detection. Paper [14] proposes a multi-sensor data fusion algorithm in WSN using fuzzy logic for the event detection. In the proposed method of fire detection, each sensor node is equipped with the diverse sensors (temperature, humidity, light, and Carbon Monoxide (CO) – used as input of fuzzy logic system) because the use of more than one sensor provides additional information on the environmental condition. The processing and fusion of these diverse sensor signals are carried out using proposed fuzzy rule-based system. The diverse sensor signals are collected at the cluster-head and fused using fuzzy rule-based method. The multiple data fusion process improved the reliability and accuracy of the sensed information and thereby minimized the false alarm rate. Author of [15] used similar logic as authors of [14]. In fire detection application they used five inputs: temperature, humidity, light, distance and CO. These fuzzy inputs are then fed to inference engine in which fuzzy rule base mange the inference for yielding a fuzzy output. In [16] novel models for fire and smoke detection, using image processing, were described. The authors used different color models for both fire and smoke. The color models were extracted using a statistical analysis of samples extracted from different type of video sequences and images. The extracted models can be used in complete fire/smoke detection system which combines color information with motion analysis. The authors used fuzzy logic and proposed a model for fire-pixel and smoke-pixel detection. The proposed model achieves up to 99.00% correct fire detection rate with a 4.50% false alarm rate. For smoke detection, a statistical analysis was carried out using the idea that the smoke shows grayish color with different illumination. The authors claim that the developed models can be used as pre-processing stage for fire or smoke detection systems. Authors of [17] developed fuzzy theory-based trust and reputation model for sensor nodes or sensor embedded nodes. Each node develops a direct reputation for each other node by making direct observations and indirect reputation between individuals, set up upon recommendations of other individuals about the neighboring nodes. The two kinds of reputations are used together to help a node evaluate the trustworthiness of the other sensor nodes, detect the malicious nodes, and assist decision-making within the wireless network. This model could be used in any WSN routing protocol, including WSNs applications in fire monitoring.

The idea of the work presented in this paper was to realize a web based system which ensures accurate and timely response in the case of fire presence. The proposed system is empowered by using fuzzy logic in decision making process. For real-time application, reliable detection and data delivery is a real challenging issue when using the WSN. It is important to note that none of the above mentioned activities considered temporal properties of the monitored events. Adding temporal semantics is especially important for WSNs because of the nature of sensor communication. Involving temporal semantic in the decision making process leads to substantial improvements like increasing accuracy of event detection and decreasing number of false alarms. Also, the confidence of event detection is higher if the temporal distance between the sensor readings is shorter and vice versa. Thus, adding temporal semantics in the decision making process is the novelty of proposed approaches compared to others. Also, the advantage of the system presented in this work is in the introduction of Sensor Web concepts. In such way, a proposed system becomes a part of the future Internet, known as Internet of things. The result of performed research is effective Sensor Web structure and intelligent decision making system, based on the data collected by a WSN, which makes possible the remote access to sensor data, its processing and visualization via the Internet.

3. Fuzzy logic usage in WSN for fire detection

One of the astonishing features of human reasoning is that it may use imprecise or incomplete information. Moreover, in the real world, there exists a lot of this kind of data and in everyday life, people use several linguistic labels to express abstract concepts [18]. Fuzzy sets and logic are introduced by L. Zadeh [19] with intention to deal with problems involving knowledge expressed in vague, linguistic terms. In other words, fuzzy logic became a mathematical discipline for describing human reasoning with rigorous mathematical notation. It is a multi-valued logic that allows the definition of intermediate values between conventional evaluations like true/false, yes/no, high/low, small/big, short/long, etc. Notions like rather long or very long, small or very small can be formulated and processed mathematically [9].

The structure of a general fuzzy logic system is shown in Fig. 2.

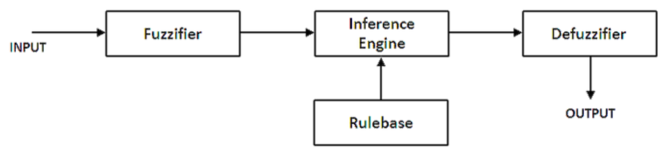

Fig. 2. The structure of a fuzzy logic system

A Fuzzy system basically consists of three parts:

- The fuzzifier;
- The inference engine; and
- The defuzzifier.

In order to determine the confidence of fire we have proposed the use of sensor nodes equipped only with temperature sensors and showed two approaches that involve temporal properties of monitored event in decision making process. As temperature sensors, two heat detectors are used: fixed temperature heat detector and rate of rise heat detector. A fixed temperature heat detector utilizes a temperature sensing element which generates an alarm condition if the temperature, within the protected area, reaches a predetermined level (e.g. 57ºC, 63ºC, 74ºC or 90ºC). The most suitable fixed temperature trigger point should be selected for the particular application. These detectors are used if high ambient temperatures exist or sudden changes in temperature occur (e.g. Kitchens, boiler rooms and foundries, etc.). A rate of rise heat detector includes a fixed temperature element, as above, and a temperature sensing element which can detect a sudden temperature change. This is a device that responds when the temperature rises at a rate exceeding a predetermined value (e.g. 8.33ºC/min, 9ºC/min or 11ºC/min). This type of detector is more sensitive than a simple fixed temperature heat detector and represents a good choice for the applications where reliable performance and early warning are critical but the environment makes smoke detection unsuitable. Both types of detectors trigger when predetermined value is exceeded. The trigger points for both types of heat detectors are determined by NFPA 72 standard [20].

Knowing that number of rules grows exponentially to the number of variables and that large rule-base might considerably slow down the event detection one of the aims of this work was to create an approach which includes temporal semantics and, at the same time, decreases the number of rules.

Thus, in this paper two experimental configurations for determining the probability of a fire in a building, based on temperature measurements, are presented together with the developed sensor node prototype used for their real time verification. Temperature sensors are chosen because they are the simplest and the most obvious sensors for fire detection, especially in the environment where other detection mechanisms (like smoke detection, flame detection, etc.) are not suitable. In addition, thermistors, used in experiments, are chosen because of its high sensitivity, low cost, reasonable accuracy and physical design (as glass bead, disk or chip thermistor) [21].

3.1. Approach 1

In the first proposed approach the system, equivalent to sensor node equipped only with a fixed heat detector, is considered. For determining the confidence of fire: previous temperature, current temperature and linguistic variable that serve as a temporal guard are used [22]. Simulations are performed using MATLAB 7.12.0 software tool. Structure of fuzzy logic system is shown in Fig. 3.

Membership functions of previous and current temperature are the same and have variables: Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH) (Fig.4). Trapezoidal and triangular shapes of membership functions are chosen because they are suitable for real-time operation (low communication complexity joined with enough accuracy).

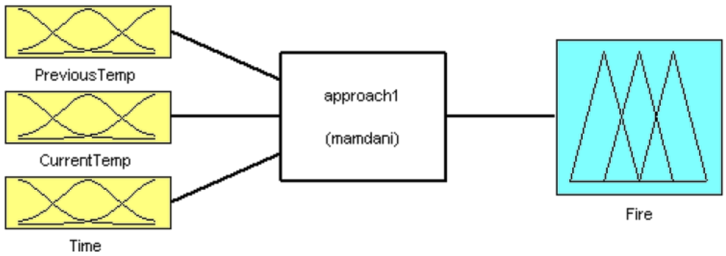

Fig. 3. The structure of a fuzzy logic system for determining confidence of fire (approach 1)

The horizontal axis represents the range of input crisp that is from 0 to 100 °C. Vertical axis is normalized and indicates degree of membership (Fig. 4).

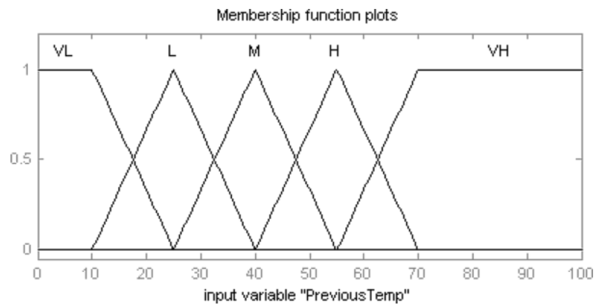

Fig. 4. Membership function of input variables “previous temperature” and “current temperature”

Variable time represents the difference in the generation times of the sensor readings. Knowing that rate of rise heat detector are activated when temperature change reaches 8.33 ºC/min, 9 ºC/min or 11 ºC/min, (according to [20]) in proposed fire detection scenario time interval of 1 min is considered as an important one and variable time is defined with two semantic values – Short (S) and Long (L) (Fig. 5). In this way the information about the period, within the sensor readings have been generated, is included in the decision process.

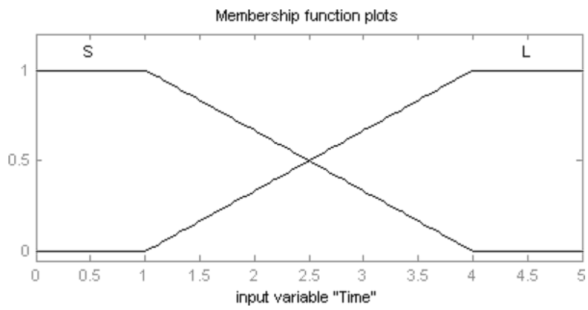

Fig. 5. Membership function of input variable “time”

Confidence of fire is defined as the output. Membership function of the output variable is divided into five levels: Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH) (Fig. 6).

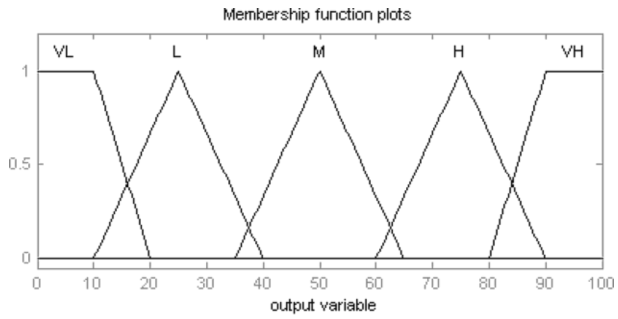

Fig. 6. Membership function of output variable “fire confidence”

The rule-base is simply a series of IF-THEN rules that relate the input fuzzy variables with the output fuzzy variables using linguistic variables, described by a fuzzy set, and fuzzy implication operators. All the rules in the rule-base are processed in a parallel manner by the fuzzy inference engine. Any rule that triggers contributes to the final fuzzy solution space [23]. Maximum number of rules in approach 1 is 50 (5*5*2). Although it is not necessary to complete all the rules, but for getting the result, all possible 50 rules are precisely defined. The first 10 rules are given in Table 1.

Table 1. First 10 rules of Fuzzy logic in approach 1

Rule	Previous temperature	Current temperature	Time	Fire confidence
	VL	VL	S	VL
	VL	VL	L	VL
	VL	L	S	L
	VL	L	L	VL
	VL	M	S	M
	VL	M	L	L
	VL	H	S	M
	VL	H	L	M
	VL	VH	S	H
	VL	VH	L	M

The fuzzy system used in the inference engine is the Mamdani fuzzy system. For every input the centroid method of deffuzification is applied to obtain a crisp output.

Fig. 7 shows the relation between time and output. It can be seen that the fire confidence decreases if the temporal distance between the sensor readings increases, and vice versa.

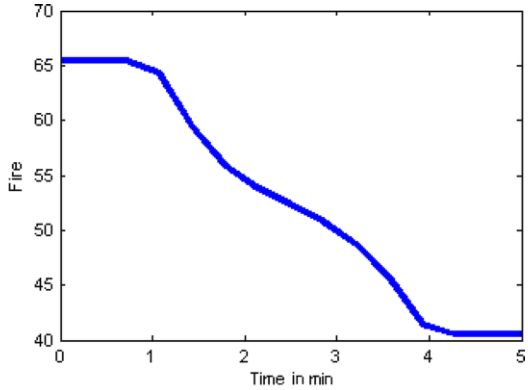

Fig. 7. Relation between fire confidence and time

Fig.8 shows the surface view – relationship between previous temperature and current temperature with output.

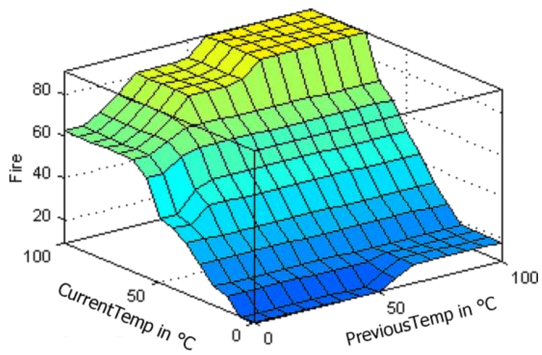

Fig. 8. Previous temperature and current temperature vs. fire confidence

3.2. Approach 2

Knowing that rate of rise heat detector responds when the temperature rise exceeds a predetermined value (e.g. 8.33 ºC/min, 9 ºC/min or 11 ºC/min) and that it is more sensitive than a simple fixed temperature heat detector, properties of fixed heat detector together with a rate of rise heat detector are combined in the second approach. In other words, current temperature and the rate of temperature change are chosen to determine fire confidence. Variable time is included together with the rate of change so now there are only two input variables: temperature and temperature difference (previous temperature minus current temperature) - delta (Fig. 9).

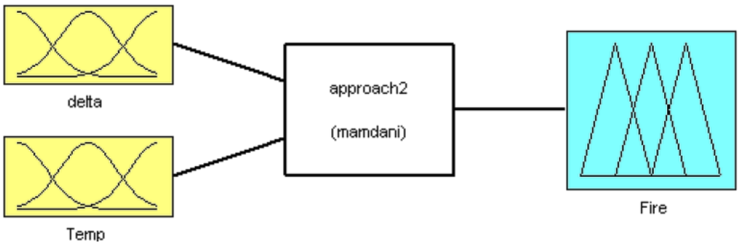

Fig. 9. The structure of a fuzzy logic system for determining confidence of fire (approach 2)

Temperature and confidence of fire are defined the same as in first approach and temperature difference has membership functions given in Fig. 10 where amount of ºC/min temperature change is presented on the horizontal axis.

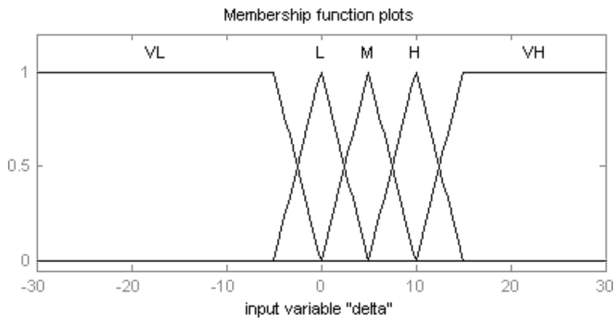

Fig. 10. Membership function of input variable "delta"

In this approach time component is also included in the process of determining fire confidence, but in this case there are two, instead of three, input variables and the number of rules is now double less – 25 (5*5). First 5 rules used in this approach are shown in Table 2.

Table 2. First 5 rules of Fuzzy logic in approach 2

Rule	Temperature difference (delta)	Temperature	Fire confidence
	VL	VL	VL
	L	VL	VL
	M	VL	M
	H	VL	H
	VH	VL	VH

Fig. 11 shows the relationship between temperature and temperature change with output.

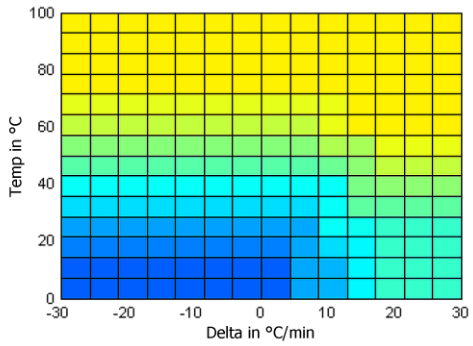

Fig. 11. Temperature and temperature change (delta) vs. fire confidence

4. Creating Sensor Web system for online data reading and visualization

Dave Evens [24] from Cisco Internet Business Solutions Group (IBSG) predicts that, by 2020, 50 billion "things" will be on Internet. In a future Internet of Things (IoT) a large number of embedded, possibly mobile computing devices will be interconnected through WSNs, constituting various autonomous subsystems that provide intelligent services for end users. Therefore, Internet connectivity in WSNs of the IoT is highly desirable, featuring sensing services at a global scale all over the world [17].

The range of sensor network applications is nearly unlimited, thus, in order to flexibly integrate any kind of sensor into any type of (software) system, the Open Geospatial Consortium (OGC) established the Sensor Web Enablement (SWE) initiative that specifies standard interfaces and encodings to remotely access, encode and exchange the sensed data [25]. Sensor Web applications became practical based on the present revolutions in computation and telecommunication hardware and are traditionally defined as a web of interconnected heterogeneous sensors that are interoperable, intelligent, dynamic, flexible and scalable. This definition implies that a Sensor Web is a hardware network of sensors; it is a new instrument concept that may be used for a wide range of applications [26]. Alternatively, the Sensor Web can be defined as a universe of network-accessible sensors, sensory data and information. In other words, the concept of the Sensor Web reflects such a kind of infrastructure for automatically discovering and accessing appropriate information from heterogeneous sensor devices over the Internet. A key challenge in building the Sensor Web is how to automatically access and integrate different types of spatiotemporal data that is observed by heterogeneous sensor devices or generated using simulation models.

Increased focus on Sensor Webs and their supporting technologies has lead to the creation of standards and encodings for data representation and interchange [27]. One approach is to view sensor nodes as Representational State Transfer (RESTful) resources that can be accessed and polled over the SWE services. REST APIs may not only be used to interact with a thing via the Web, also website representations of things may be provided to display dynamically generated visualizations of data gathered by the thing [28]. Moreover, exchanging messages using the lightweight JavaScript Object

Notation (JSON) data format instead of the Extensible Markup Language (XML), one can trigger a good extension to the SWE initiative [29].

To test two aforementioned approaches a sensor node prototype is created, precisely a prototype of the Sensor Web node. This sensor node was exposed to temperature changes created to simulate an environment of temperature rise in real time.

A typical architecture of a sensor node, used to create a prototype model is shown in Fig. 1. Unlike typical architecture, sensor node prototype proposed in this paper, is composed of sensing unit, which includes temperature sensors and analog to digital converter (ADC), and processing unit which includes processing and communication unit. The purpose is to programmatically control device in a building in such a way that user, equipped with inexpensive hardware and open source software, may create own solution which will meet his needs.

Thus, the Raspberry Pi type B is used as the processing unit. The Raspberry Pi is an inexpensive, fully customizable and programmable small computer, supporting a large number of input and output peripherals and network communication, making it a perfect platform for interfacing with home appliances and devices.

A detailed description of the hardware and software capabilities of Raspberry Pi is described in [30]. One of its main advantages is the integrated General Purpose Input and Output (GPIO) that is used to perform communications with elements of sensing units.

In this section, the emphasis is put on: sensing unit implementation, reading and processing the sensor data. Using this technology, in monitoring and determining the probability of having a fire in the building, a complete system is designed and developed. The rest of the paper is devoted to its more detailed description.

4.1. Sensing unit and temperature reading

The prototype sensor unit is composed of two analog temperature sensors (thermistor models: B57045k10 [31] and 10kNTC [32] chosen based on their price, availability and precision) and an 8-bit ADC (model: PCF8591 [33]).

Sensors' characteristics are shown in Table 3, where T_0 and R_{T0} parameters are reference temperature and resistance respectively, used for parameter B calculation. For both sensors T_0 is 25 °C, and R_{T0} is 10000 Ω. B parameter can be calculated empirically, but usually all three parameters, T_0, R_{T0} and B, are given in sensor data sheet. $\Delta R_R/R_R$ is a standard sensor deviation.

Table 3. Sensors' parameters

	B57045k10	10kNTC
T_0	25 °C	25 °C
R_{T0}	10 000 Ω	10 000 Ω
$B(_{25/100,25/50})$	4300 K	3950 K
$\Delta R_R/R_R$	± 10%	± 1%
Range	-55 – 125 °C	-20 – 105 °C
Additionally		waterproof

ADC is necessary for the communication with the processing unit. For this purpose an 8-bit ADC which provides 256 steps is used. In [34] it is shown that electrical resistance of thermistor can be obtained using a voltage divider consisted of two resistors, one with variable and unknown resistance and other with fixed and known resistance. In the prototype model fixed resistance of 10 000 Ω and sensor and ADC power supply in the range of 3.27V-3.3V are used.

There is also a need to create a driver on processing unit that allows reading information from the ADC and converting them into a form suitable for further processing. ADC is connected to the processing unit via GPIO ports - via the I^2C protocol [35], where thermistor voltage is read. The thermistor temperature can be computed with the Steinhart-Hart equation [36] with the B parameter:

$$\frac{1}{T} = a + b\ln(R) + c\ln^3(R) \tag{1}$$

For

$$a = \left(\frac{1}{T_0}\right) - \frac{1}{B}\ln(R_0), \quad b = \frac{1}{B}, \quad c = 0 \tag{2}$$

Steinhart–Hart equation is:

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B}\ln\left(\frac{R}{R_0}\right) \tag{3}$$

Temperature T is expressed in Kelvin. If parameters T_0, R_0, B and current resistance of thermistor are known, then the temperature can be calculated.

4.2. Sensor Web software architecture

In order to meet the basic requirements of a Sensor Web structure prototype, it is necessary to enable the distribution of sensed data over the Internet. To fulfill this requirement, it is necessary to set up a service on processing unit that will be the mediator between the sensor driver and an end-user or a customer. In order to enable JAVA prototype implementation it was necessary to preinstall the Apache Tomcat 7 server on the processing unit. The need for simple service support with optimal number of resources qualified the REST services as a primary choice. Service implementation, where every action is a resource and has a unique URI, creates the interface via which is accessed to the sensor data. Thus, for the temperature readings from sensors used in the prototype model, two URI address are provided:

```
(server adress)/RPISensorWeb/sw/b57045k10
(server adress)/RPISensorWeb/sw/ntc10k
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For communication between the service and the client, due to its simplicity, processing speed and low permeability, the JSON notation is used, while communication itself is realized via HTTP/HTTPS protocol.

The infrastructure diagram of prototype model is shown in Fig. 12. The diagram is divided into three main components: the client, the communication channel and service which is a Sensor Web element. At the client side, it is important to note that it is possible to use any client, that supports the execution of Java programs, to access a Sensor Web. The majority of currently used systems posses this support by default. Communication channel used to access the Sensor Web is the Internet itself – based on the TCP/IP protocol. Sensor Web element includes all remaining elements, communication unit (which owns the IP address), the CPU (which is able to collect, process and disseminate data), and sensors with Analog to Digital Converter (ADC).

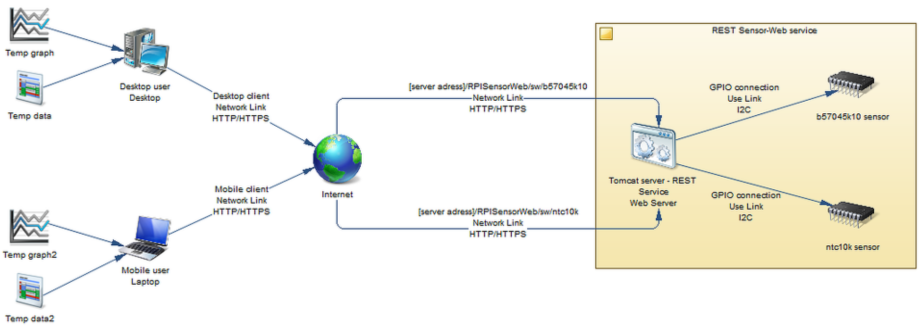

Fig. 12. Infrastructure diagram of Sensor Web prototype system

4.3. Processing data from Sensor Web

For the analysis of data from the Sensor Web, an application that performs real-time data collection, processing and visualization of data from the sensor is developed. Data processing includes the residential fire confidence data based on fuzzy rules defined in the previous section.

Since the Java programming language is used to implement the client, prediction based on pre-defined rules is calculated with a help of JFuzzyLogic library [37]. JFuzzyLogic library implements the Fuzzy Control Language (FCL) according to IEC 61131-7 specification [38] and the semi-automatic “FIS to FCL” converter for the easier way to test the model created in MATLAB software tool 7.12.0. is developed.

In Fig. 13 a visualization segment of the measured data with B57045k10 sensor is shown.

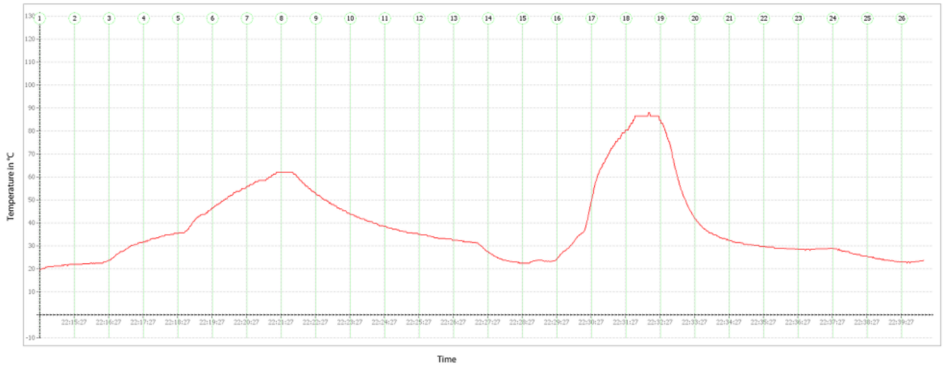

Fig. 13. Graphical visualization of measured data

Measurement time is associated to x-axis while the y-axis shows temperature values. Depending on the measured interval, there is a possibility of adjusting the measurement range and sampling time. In Fig. 13, the predefined sampling time is 60 sec. For the purpose of information processing, in the data visualization process are implemented markers that mark the moment when the sample was recorded (Fig. 14).

Legend:
- Very low critical
- Low critical
- Medium critical
- High critical
- Very high critical

Datum mjerenja: 01.08.13

Start at: 22:14:27

R.br.:	Time:	PrevTemp:	CurrTemp:	Delta:	Poss.1:	Poss.2:	Deg.:	
1.	22:14:28	19,40	19,40	+ 00,00	19,98	25,00	A1(1[00,37] 3[00,37] 11[00,37] 13[00,63])	A2(2[00,37] 7[00,63])
2.	22:15:27	19,40	21,95	+ 02,55	22,03	21,71	A1(1[00,20] 3[00,37] 11[00,20] 13[00,63])	A2(2[00,20] 3[00,20] 7[00,49] 8[00,51])
3.	22:16:27	21,95	23,87	+ 01,92	23,96	23,84	A1(1[00,08] 3[00,20] 11[00,08] 13[00,80])	A2(2[00,08] 3[00,08] 7[00,62] 8[00,38])
4.	22:17:27	23,87	31,51	+ 07,64	36,37	48,83	A1(3[00,08] 5[00,08] 13[00,57] 15[00,43])	A2(8[00,47] 9[00,53] 13[00,43] 14[00,43])
5.	22:18:27	31,51	35,44	+ 03,93	40,35	41,01	A1(13[00,30] 15[00,57] 23[00,30] 25[00,43])	A2(7[00,21] 8[00,30] 12[00,21] 13[00,70])
6.	22:19:27	35,44	46,54	+ 11,10	61,41	80,86	A1(15[00,30] 17[00,30] 25[00,56] 27[00,44])	A2(14[00,56] 15[00,22] 19[00,44] 20[00,22])
7.	22:20:27	46,54	55,49	+ 08,95	75,53	86,78	A1(27[00,56] 29[00,03] 37[00,44] 39[00,03])	A2(18[00,21] 19[00,79] 23[00,03] 24[00,03])
8.	22:21:27	55,49	62,08	+ 06,59	81,37	81,37	A1(37[00,53] 39[00,47] 47[00,03] 49[00,03])	A2(18[00,53] 19[00,32] 23[00,47] 24[00,32])
9.	22:22:27	62,08	53,17	- 08,91	69,49	70,45	A1(35[00,12] 37[00,53] 45[00,12] 47[00,47])	A2(11[00,12] 16[00,88])
10.	22:23:27	53,17	44,27	- 08,90	58,60	58,60	A1(25[00,12] 27[00,12] 35[00,72] 37[00,28])	A2(11[00,72] 16[00,28])
11.	22:24:27	44,27	38,47	- 05,80	45,83	46,08	A1(23[00,10] 25[00,72] 33[00,10] 35[00,28])	A2(6[00,10] 11[00,90])
12.	22:25:27	38,47	35,07	- 03,40	40,53	40,53	A1(13[00,10] 15[00,10] 23[00,33] 25[00,67])	A2(6[00,33] 7[00,32] 11[00,67] 12[00,32])
13.	22:26:27	35,07	32,56	- 02,51	37,57	37,55	A1(13[00,33] 15[00,33] 23[00,50] 25[00,50])	A2(6[00,50] 7[00,50] 11[00,50] 12[00,50])
14.	22:27:27	32,56	27,45	- 05,11	31,97	30,74	A1(13[00,50] 15[00,16] 23[00,50] 25[00,16])	A2(6[00,84] 11[00,16])
15.	22:28:27	27,45	22,58	- 04,87	22,85	25,00	A1(11[00,16] 13[00,84] 21[00,16] 23[00,16])	A2(1[00,16] 2[00,03] 6[00,84] 7[00,03])
16.	22:29:27	22,58	24,19	+ 01,61	24,26	24,20	A1(1[00,05] 3[00,16] 11[00,05] 13[00,84])	A2(2[00,05] 3[00,05] 7[00,68] 8[00,32])
17.	22:30:27	24,19	48,96	+ 24,77	64,17	83,25	A1(5[00,05] 7[00,05] 15[00,40] 17[00,60])	A2(15[00,40] 20[00,60])
18.	22:31:27	48,96	79,22	+ 30,26	91,38	92,20	A1(29[00,40] 39[00,60])	A2(25[01,00])
19.	22:32:27	79,22	84,84	+ 05,62	92,20	91,96	A1(49[01,00])	A2(23[00,88] 24[00,12])
20.	22:33:27	84,84	42,11	- 42,73	55,10	55,10	A1(45[00,86] 47[00,14])	A2(11[00,86] 16[00,14])
21.	22:34:27	42,11	32,56	- 09,55	37,57	37,57	A1(23[00,50] 25[00,50] 33[00,14] 35[00,14])	A2(6[00,50] 11[00,50])
22.	22:35:27	32,56	29,80	- 02,76	35,36	35,00	A1(13[00,50] 15[00,32] 23[00,50] 25[00,32])	A2(6[00,55] 7[00,45] 11[00,32] 12[00,32])
23.	22:36:27	29,80	28,45	- 01,35	32,70	32,52	A1(13[00,68] 15[00,23] 23[00,32] 25[00,23])	A2(6[00,27] 7[00,73] 11[00,23] 12[00,23])
24.	22:37:27	28,45	28,79	+ 00,34	32,92	32,92	A1(13[00,75] 15[00,25] 23[00,23] 25[00,23])	A2(7[00,75] 8[00,07] 12[00,25] 13[00,07])
25.	22:38:27	28,79	25,16	- 03,63	25,51	25,52	A1(13[00,75] 15[00,01] 23[00,25] 25[00,01])	A2(6[00,73] 7[00,27] 11[00,01] 12[00,01])
26.	22:39:27	25,16	23,23	- 01,93	23,43	25,00	A1(11[00,12] 13[00,88] 21[00,01] 23[00,01])	A2(1[00,12] 2[00,12] 6[00,39] 7[00,61])

Stop at: 22:40:05

Fig. 14. Visualization of processed sensor data

In this way, data analysis becomes simpler and more detailed. Each sample corresponds to one of the markers, shown on the chart in Fig. 14, and contains information about: the time when the sample was taken; the previous temperature; the current temperature; and the difference between the current and the previous temperature (Delta = CurrTemp - PrevTemp).

Appr.1 and Appr.2 represent the probability of fire based on the defined rules of fuzzy logic in Approach 1 and Approach 2, respectively. As it can be seen from Fig. 14 different colors indicate the probability of fire which is divided into 5 segments with the step of 20% (0-20 - Very low critical, 20-40 - Low critical, etc.). To analyze the validity of the predefined fuzzy logic rules the ability of JFuzzyLogic libraries to display the probability of rules that are selected in the decision making process is used. Fig. 14 shows these results for both approaches.

Comparative analysis of the data from Fig. 13 and Fig. 14 makes it possible to detect the crucial moments of fire occurrence in some parts of the samples, especially in areas where the rise of temperature in time is high. It can be seen that both approaches yield similar results, and their analysis will be carried out in detail in the next section.

5. Measurements and results analysis

In this section obtained simulation results are presented and discussed.

Fig. 15 and 16 present measured current and previous values of temperature and fire confidences obtained using approach 1 for both types of temperature sensors. In this diagram, horizontal axis presents the measurement number while temperature values are shown on vertical axis. Sensor readings are recorded each 60s (time is short).

Temperature sensor model 10kNTC is used to simulate temperature changes at lower temperatures. Fig. 15 and 16 show that first approach for determining confidence of fire smoothly "follows" previous and current temperature and that there are no extreme peaks.

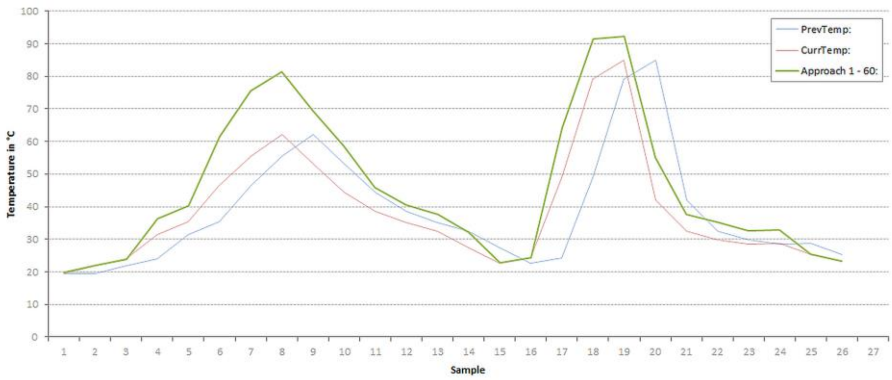

Fig. 15. Measured values of previous and current temperature and obtained fire confidence using approach 1 (model B57045k10)

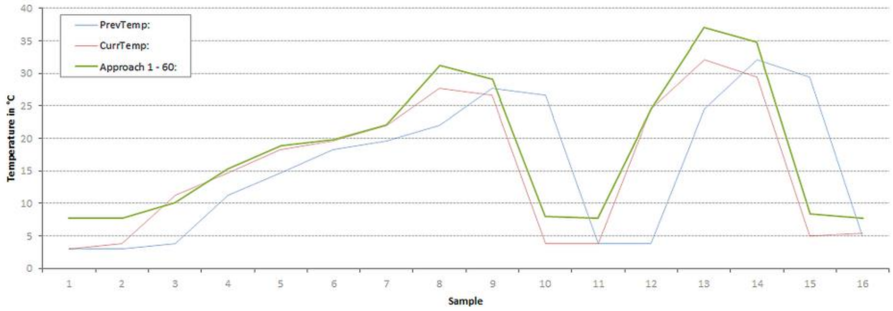

Fig. 16. Measured values of previous and current temperature and obtained fire confidence using approach 1 (model 10kNTC)

Assumed that the same sensor readings are recorded each 2.5th and 4th minute, obtained fire confidences would be less compared to one shown in Fig.15 and Fig.16.

Thus, from Fig. 17 and Fig. 18 it can be seen that the confidence of determining fire presence is higher if the temporal distance between the sensor readings is shorter and vice versa.

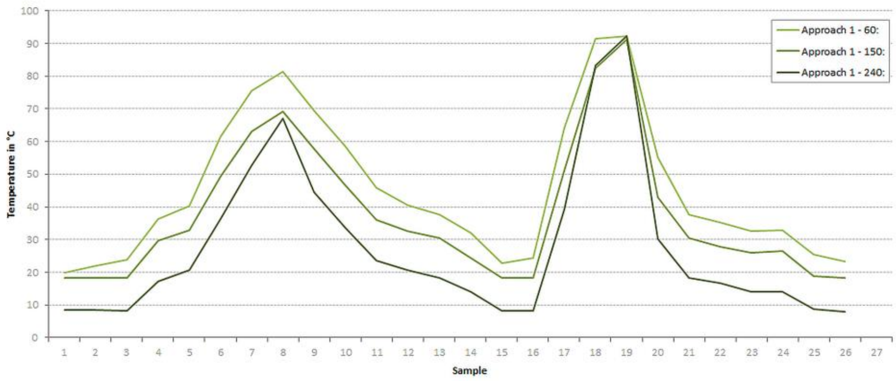

Fig. 17. Obtained fire confidence vs. time of sensor readings (model B57045k10)

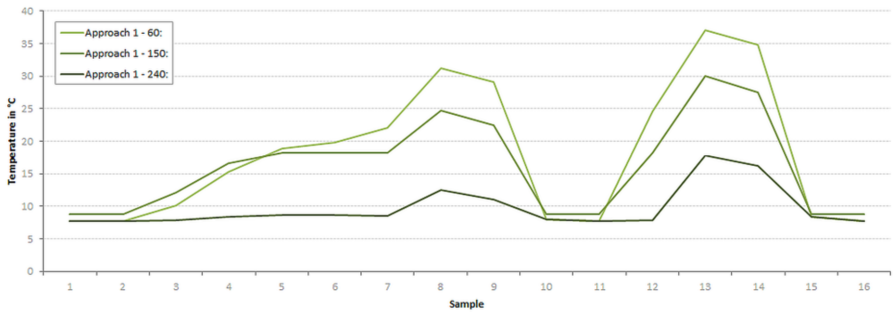

Fig. 18. Obtained fire confidence vs. time of sensor readings (model 10kNTC)

Fig. 19 and 20 show temperature, temperature change (delta) and fire confidence obtained using approach 2. From presented figures it can be seen that the second approach is more sensitive in cases when the temperature rises are very high.

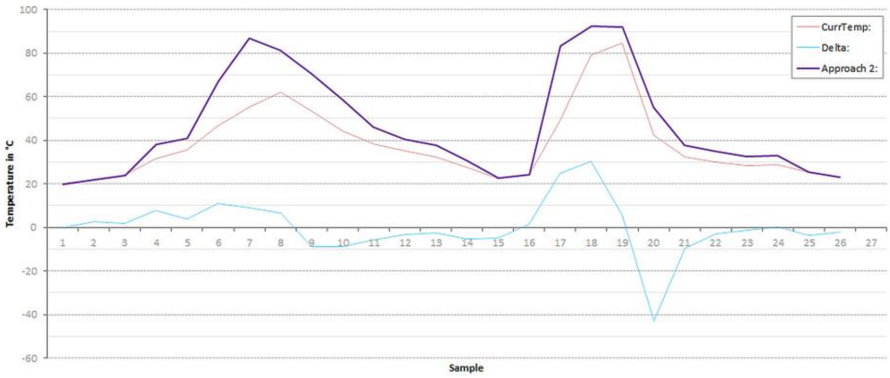

Fig. 19. Measured values of temperature and temperature change and obtained fire confidence using approach 2 (model B57045k10)

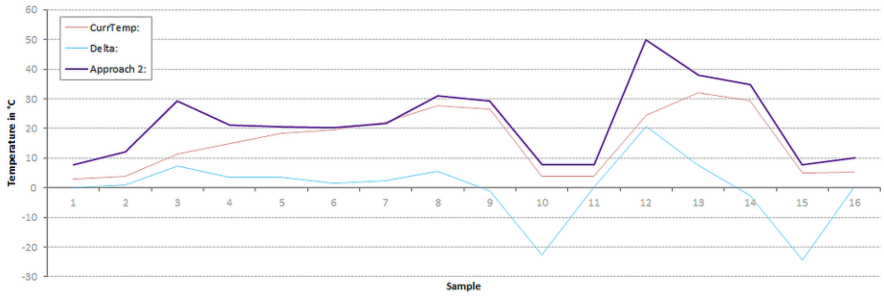

Fig. 20. Measured values of temperature and temperature change and obtained fire confidence using approach 2 (model 10kNTC)

Fig. 21 and 22 show obtained confidences of determining fire confidences using above proposed two approaches.

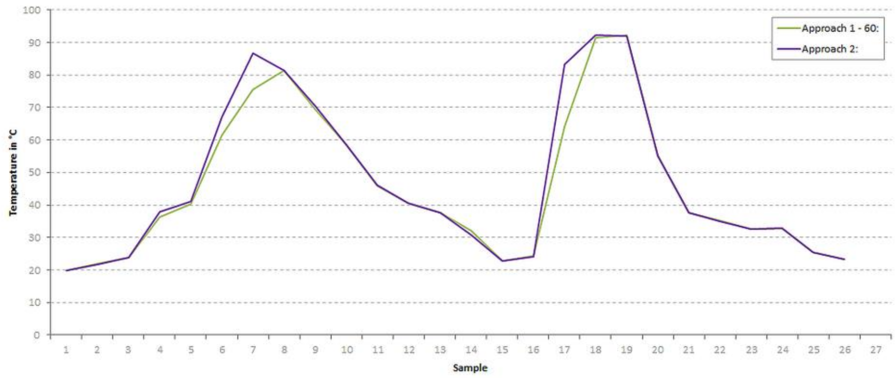

Fig. 21. Compared obtained fire confidences using approach 1 and approach 2 (model B57045k10)

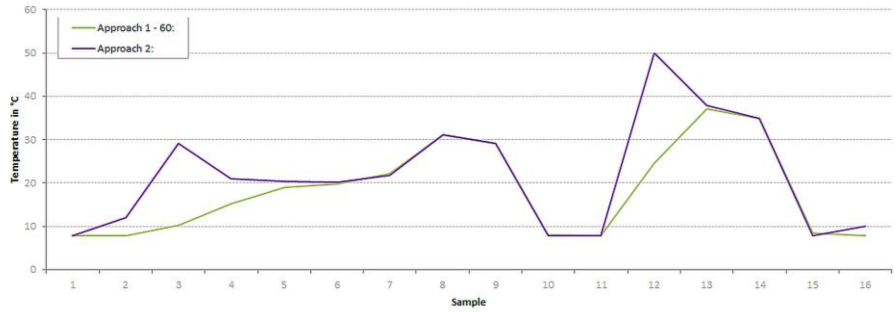

Fig. 22. Compared obtained fire confidences using approach 1 and approach 2 (model 10kNTC)

For temperature sensor model B57045k10, used for measuring high temperatures, Fig. 21 shows that there is no significant deviation in obtained fire confidences using proposed approaches. Unlike Fig. 21, Fig. 22 shows that for lower temperatures, the difference between two approaches is more noticeable, especially in the moments of high temperature rises. It can be concluded that the fuzzy logic system has an ability to, very efficiently and accurately, distinguish between a normal condition and fire condition.

In order to realize if two datasets:

Group A: obtained fire confidence using approach 1, and

Group B: obtained fire confidence using approach 2

are statistically different, a two-sample t-tests are performed (Table 4. and Table 5.) [39].

Table 4. Two-sample t-test of datasets presented in Fig. 21

Descriptive Statistics			
	Mean	Standard Deviation	n
Group A	45.4785	22.1817	26
Group B	46.92	24.0699	26
Independent Samples t-Test			
t-Statistic	-0.2246	Result	
Degrees of Freedom	50	Do not reject the null hypothesis	
Critical Value	2.0086	Conclusion	
95% Confidence Interval	[-19.349, 22.2321]	Group A is not significantly different from Group B, t(50) = -0.2246, p > .05.	

Table 5. Two-sample t-test of datasets presented in Fig. 22

Descriptive Statistics			
	Mean	Standard Deviation	n
Group A	18.1425	10.6183	16
Group B	21.7894	12.7878	16
Independent Samples t-Test			
t-Statistic	-0,8776	Result	
Degrees of Freedom	30	Do not reject the null hypothesis	
Critical Value	2.0423	Conclusion	
95% Confidence Interval	[-7.0878, 14.3816]	Group A is not significantly different from Group B, t(30) = -0.8776, p > .05.	

The outputs obtained from running a t-test is the probability (“p-value”) of getting the t-statistic calculated for datasets. As a general rule, if p-value is less than the critical value of .05 it means that the results are significant and therefore support an alternative hypothesis which states that there is a difference in the distributions of two datasets. (Although in theory and practice many numbers can be used for alpha, the most commonly used is 0.05. The reason for this is mainly in both: the consensus on its appropriateness, and the fact that it is accepted as the standard trough the history.)

Both t-test, presented in Tables 4 and 5, show that obtained fire confidence using approach 1 is not significantly better than fire confidence of approach 2.

To check how sensor precision influence on fire confidence output, in this paper is assumed that sensor B57045k10 has standard deviation ± 2 °C. Fig. 23 and Fig. 24 show that this error doesn't have significant influence to output results in the case of both proposed approaches.

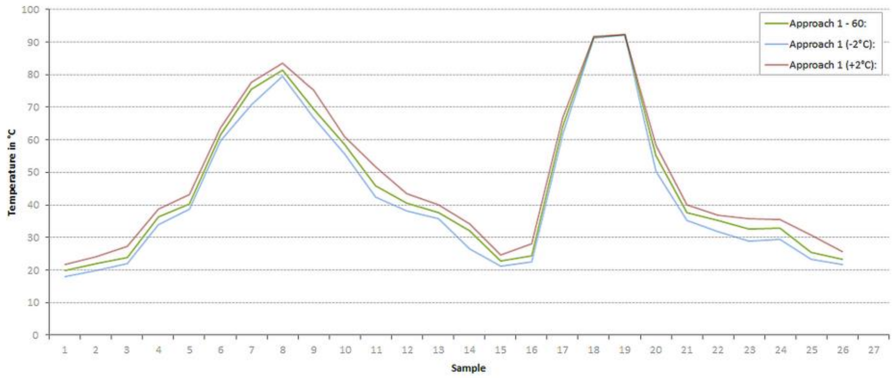

Fig. 23. Sensor fluctuations impact to output – Approach 1 (model B57045k10)

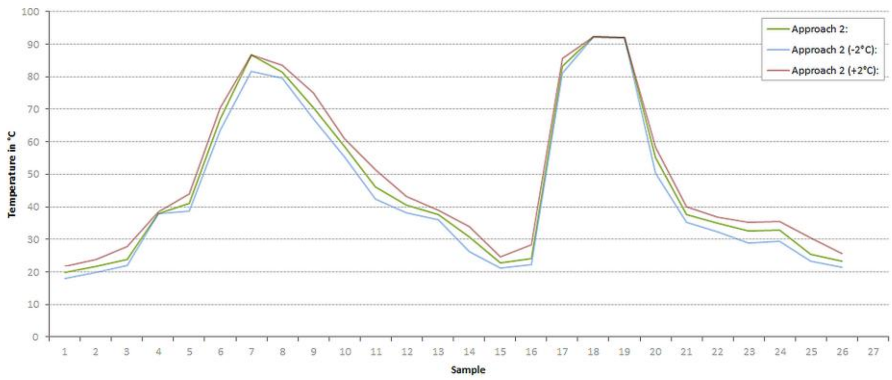

Fig. 24. Sensor fluctuations impact to output – Approach 2 (model B57045k10)

Fig. 23 and Fig. 24 confirm that compared to using crisp values, fuzzy logic allows the detection algorithm to maintain a high accuracy level despite fluctuations in the sensor values what provides fast and accurate event detection and decreases the number of false alarms.

In a case when there is a need to further improve accuracy, it is necessary to pay attention to the range of the ADC, and the temperature at which the ADC works (in this case from -40 °C to 85 °C). Further improvement can be made by replacing the ADC with one with high resolution, 10-bits and more, or choosing more accurate (precise) temperature sensor.

According to performed statistical tests and above presented figures it is obvious that both approaches deliver quite good results regarding the model of temperature sensor used. Besides that, it is clear that both approaches yield similar results, but including temporal semantic together with temperature change in approach 2 fuzzy logic system becomes more sensitive to high temperature rises and has double fewer rules compared to the first one.

Considering that the main disadvantage of using fuzzy logic in WSN is the number of rules, this process is reasonable and it will lead to less energy and memory nodes' consumption, reducing transmission costs and also making critical event detection faster. Also, included temporal properties of the system have shown that the fire confidence output is higher if the temporal distance between the sensor readings is shorter and vice versa. Also, fluctuation analysis shows systems' tolerance for a wide range of sensors, allowing the construction of low-cost Sensor Web nodes.

The obtained results of approaches presented in this work are not compared with the results of other related works. The reason for it is the fact that other approaches use several diverse sensors for decision making (not just temperature sensors) and in order to compare results it is necessary to realize the same or hierarchical fuzzy system which would include temporal semantic, what will be one of the directions of future work.

The classical way to implement the fuzzy system is in a fully software manner, like it is the case with the implementations described in this paper. Such an approach is most general, easiest and is the least expensive among all the methods used to realize a fuzzy system. The main disadvantage is that software based approach is the slowest among all [40]. Because of this, many authors propose hardware realizations of fuzzy processors and controllers which are used to address the real time problems of fuzzy logic based system. Authors of [41] designed and implemented the fuzzy temperature controller without using any special software tool. The final hardware is a stand-alone system which uses a small number of rules. The design approach presented in this paper minimizes the total cost of hardware and software design. The authors also state that in these systems the design emphasis should be more focused on the inference engine performance and defuzzification units, because of the complexity of computations they have to handle, and that the optimization in these units results in a significant improvement in the overall system performance.

As it is already stated, the disadvantage of using fuzzy logic is that the number of rules grows exponentially to the number of variables and storing the rule-base might require a significant amount of memory. To solve this problem, it is necessary to develop the efficient rule-base reduction techniques. For the approach 1 in [33] FURIA (Fuzzy Unordered Rule Induction Algorithm) [42] is applied. Applying FURIA, rule base is significantly reduced and data analysis for this measurement shows that decreased rule base has slightly lower accuracy in contrast to a full rule base system, which means that, by reducing a number of rules, system's energy and memory consumption can be decreased, transmission costs can be reduced and critical event detection made faster.

Further improvements of two proposed approaches consider implementing other rule reduction methods (separating the rule base, combining rules with similar outcomes, using incomplete rule base, etc.) and creating hardware realizations of fuzzy processors and controllers, which will be the one of the directions of our future research.

6. Conclusion

The use of fuzzy logic in WSNs is a promising technique since it allows combining and evaluating diverse parameters in an efficient manner. Fuzzy logic is a very promising approach because the execution requirements can be easily supported by sensor nodes improving the overall network performance. In order to increase event detection and further decrease the number of false alarms, the temporal properties of the monitored events have to be involved in decision making causing the number of decision supporting rules to increase. Focusing on the aim to increase accuracy and decrease false alarms, two approaches for determining confidence of fire, including temporal semantic, are presented in this paper and simulated via created sensor node prototype. The first approach is based on previous and current temperature sensor readings inside the defined time interval, while the second one introduces two linguistic variables: temperature and rate of temperature change that encapsulate time variable. Both approaches are first modeled and tested in MATLAB.

The simulation results show that confidence of determining fire confidence is higher if the temporal distance between the sensor readings is shorter and vice versa. Besides that, two-sample t-test and simulation obtained results show that both approaches give almost the same results, but second approach has double fewer rules compared to previous one and is more sensitive to temperature rises.

Considering that the main disadvantage of using fuzzy logic in WSN is a large number of rules (what is not appropriate for energy and memory limited sensor node devices) and that storing a full rule-base on every node might not be reasonable because constantly traversing of a large rule-base might considerably slow down the event detection and drain energy resources, the second approach (less number of rules) appears to be a better choice (compared to approach one). In such way, the fuzzy approach with fewer rules in the rule base enables saving the power as well as life of battery used for WSN node. Thus, it can be stated that by using only the rules which are important for a particular node instead of storing a full rule-base on every node, the power consumption in proposed approaches has been reduced compared to full rule-base approaches (the processor deals with less data [43-45]).

In general, the inclusion of temporal and distance semantics in fuzzy approaches, increases event detection or accuracy of decision making process, but at the same time increases rule base. In approaches proposed in this paper only temporal semantic is included in order to enable timely and accurate response, what is crucial in firefighting scenario. Included temporal semantic leads to increased event detection and, subsequently decreases the number of false alarms, compared to other systems which doesn’t include temporal semantic. In addition, based on the fuzzy nature of the solution, the false alarms are detected within a short time interval. Based on the same principle, the node failure is detected very quickly, because of the nature of Steinhart-Hart equation and the hardware system (large negative temperature readings).

Furthermore, the performed analyses have also confirmed that fuzzy logic allows detection algorithm to maintain a high accuracy level despite fluctuations in the sensor values. This feature provides fast and accurate event detection and decreases the number of false alarms and induces cheaper Sensor Web structure implementation.

The approaches described in this paper, based upon inexpensive hardware and open source software, enables the effective creation of a Sensor Web structure and intelligent decision making system, based on the data collected by a WSN, making possible the remote access to sensor data, its processing and visualization via the Internet. This may guarantee the critical events detection should be delivered to the end user as soon as possible and within the reach of the global network (Internet).

Each of the above proposed approaches can be further optimized reducing number of rules using other well known rule reduction methods (separating the rule base, combining rules with similar outcomes, using incomplete rule base - e.g. measuring only rise and not decrease of temperature, etc.). Discarding normal values and transmitting only anomaly values to the central server should make early fire detection possible. Creation of hierarchical fuzzy system or fuzzy network, with several diverse sensors, including temporal and distance semantic, as well as reducing number of rules and impact of reduction rule base to confidence level, will be the main directions of our future researches. Besides that, the directions of future work will be to enhance the speed of the software based fuzzy system via fuzzy processors based hardware realization.

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