Sensitivity of water meters to small leakage

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Sensitivity of water meters to small leakage

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ABSTRACT

Water leakage beyond the meter at the household level is becoming an emerging problem in a world where water must be respected and saved. More than public awareness campaigns for citizens, automatic leakage detection could give in the future the best results. Domestic water consumption will be continuously monitored by smart meters able to distinguish between normal absorption and leakage. Nowadays, some research prototypes of smart water meters were designed for continuous monitoring aimed to collect measurements and send them to a central unit for developing statistics on consumptions and alarms. In this paper, the authors propose a battery-powered visual smart device that could be a good starting point to generate leakage alarms at the household level. After a brief description of state of the art, the paper at first faces the problem of the leakage detection dependence on meter sensitivity. Then, an image-based technique for automatic "null consumption detection" to be applied both to the register last digit and to a needle of water meters is tested on three different water meters. Finally, experimental results confirm that this image-based technique, allowing the automatic detection of Periods With Null Consumption, can be very useful for water leakage detection algorithms.

1. Introduction

The most important natural substance for the human being life is clean water. Nevertheless, water leakage is widespread both in the distribution network for the reason of obsolescence, corrosion, etc., and at the household level, after the meter, due to dripping taps, toilet cisterns faults, negligence, etc. The technical community has been urged to work to the former because it damages distribution companies, and numerous solutions have already been proposed [1,2]. Until now, less importance or prominence has been given to the latter type of leakage because consumers pay it. In recent years, national and continental authorities have increasingly paid attention to problems concerning the resource monitoring aimed to avoid unnecessary waste and reduce consumption. This trend has extended the interest also to leakage after the meter. In a first study (1999) [3] it was reported that in 1188 monitored houses, the average leakage ranged between 110.2 L/d (21.9 gphd, gallons per household per day), and about 342.2 L/d (90.4 gphd) in about the 8.5% of the sample. The Water Research Foundation's (WRF) successive report (2016) [4] provides an updated and expanded assessment of water use. The report authors identify some variations in water use, providing detailed information and data on changes since the Residential End Uses of water report done in 1999 (REU1999). The report assesses a decline of about 22% respect to 1999 in water use across the residential sector, even as populations increase. Despite use decrease, leakage still amounts to 13% of indoor household water use, consisting of an average absolute value of about 67.4 L/d (17.8 gphd).

In a world where clean water is going to become an increasingly rare and precious good, no cause of waste can be longer acceptable, regardless of the economic interests that are affected.

In support of this thesis, several scientific and technical papers have been published in the last years that try to tackle the problem of small water leakage detection at the household level; still, none of these seem to be conclusive. In [5], some consumption profiles concerning a local small community network are reported. Data must be collected in a data center to detect suspect consumers and to conduct an audit to identify leakages. The water meter is an Arduino-based prototype that is very far from series production, and no consideration of battery problems for domestic application has been made even if three solutions for sending information to the central data center are proposed. Finally, no leakage detection algorithm is proposed.

A methodology for leakage detection at two scales (end-user and District Metered Area) is reported in [6]. Water smart meters are traditional water meters whose impulse sensor output is acquired by an impulse sensor and transmitted via a radio frequency (169 MHz) to gateways. The Advanced Metering Infrastructure, AMI, to get readings and detect leakage was installed, as an experimental testbed, at the

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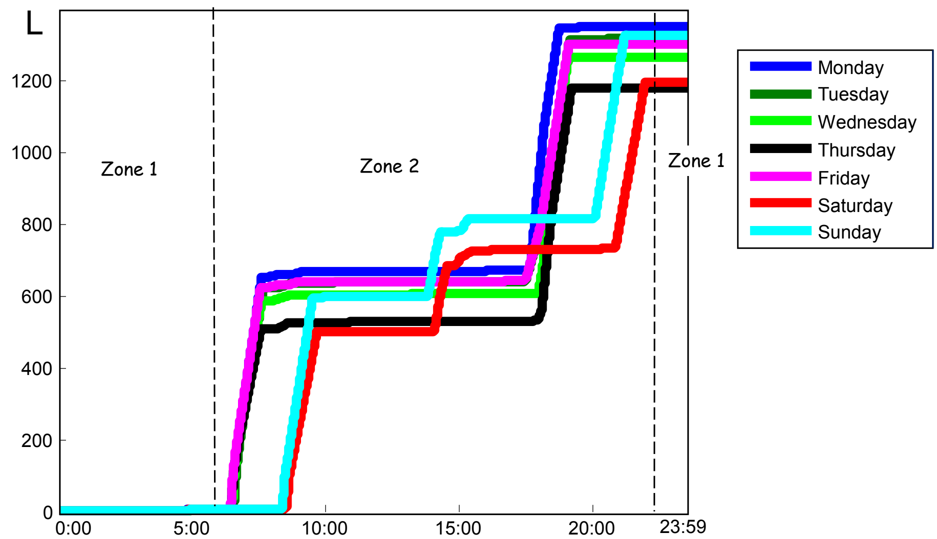

Fig. 1. Daily consumption curves concerning a week.

University Campus. Neither energy consumption nor transmission efficiency is evaluated. Smart meters detect leakage and send alerts to the central unit by analyzing the user consumption profile. They based this approach on the analysis of hourly, daily, and seasonal variation in the consumption profile, including the evaluation of the minimum night flow. On this basis, meters send an alert when the leak probability exceeds a too simple threshold: the average plus two standard deviations.

Sithole at al. [7] propose a low-cost smart water meter prototype based on a microcontroller (Arduino). It detects water leakage for each time the flow rate is constrained between 0 and 40 L per hour for more than five seconds. Both the threshold and the time interval seem to be inadequate.

More reliable seems the solution proposed in [8], where leakage detection relies on continuous offtake monitoring and on setting daily limits. Continuous offtake times are divided into time zones (for example, day/night), with single boundaries being entered either manually or based on, so-called, self-learning mode. Even though simulation tests seem to give encouraging results, the smart meter is not prototyped yet.

In summary, the authors note that two main topics miss in more recent literature: i) sensitivity of domestic water meters has not been considered at all; ii) smart meter communication capability must be mainly evaluated in terms of coverture range and battery life.

The former lack affects the reliability of whatever leakage detection algorithm can be thought: all consumptions lower than the sensitivity of water meters cannot even be detected, let alone classified. Some studies on water consumption at the household level agree, considering that background leakage already occurs at 1 L/h flow rate and less, would require meter sensitivity in the range of [0.1, 0.5] L/h. Based on the authors of [9] instead, who studied the behavior of over 22′000 households, the most common leakage rates are between 20 and 10 L/h, and over 49% of leakages are 20 L/h. This last data would be comparable with the typical value of sensitivity of domestic water meters [20, 40] L/h.

The latter lack determines the viability of proposals: smart water meters must be battery-powered devices that grant at least some years of battery life. Although still not widespread, various types of smart meters can either direct access to the Internet or connect to a gateway through short-range antennas. While distribution network's leakage detection algorithms always assume that measured data be processed centrally because they come from few big water meters that can be featured with high capacity batteries, in case of domestic consumption data should come continuously from many measurement points, one per user. These specifications would generate bandwidth problems for short-range physical channels and overload problems for GSM networks and server computers. Also, the continuous transmission of rough data would be an additional load, hardly compatible with battery capacities of domestic devices that cannot exceed a few Ah for volume reason.

On this basis, the authors conclude that the first two steps towards leakage detection at the household level must be the following: (a) sensitivity characterization of commercial, domestic water meters; (b) prototyping of battery devices with onboard processing capabilities suitable for implementing detection algorithms.

In 2018 the European Association of National Metrology Institutes (EURAMET), within the European Metrology Program for Innovation and Research (EMPIR), funded the Joint Research Project (JRP) "17IND13 Metrowamet – Metrology for real-world domestic water metering", that is aimed to study and to test smart metering solutions to solve the problem of leakage detection at the household level. The authors are among the participants to the EMPIR JRP 17IND13 Metrowamet, thanks to their experience on wM-Bus at 169 MHz and on water smart meters [10–14].

Data on both water meter old installations and today roll out policies confirm that mechanical water meters are still far from being put aside. Based on [15] the authors compared an ultrasound digital flow meter with a multijet water meter to evaluate their aptitude to measure small flows. Results were encouraging for both them, even if with some limits: too high energy consumption the former and scarce sensitivity the latter. In the following, after a summary of the scientific literature in the field, the authors will describe how they improved the sensitivity that can be obtained by mechanical water meters in detecting "Periods With Null Consumption" through image-based techniques. Experimental tests were carried out by featuring domestic analogic water meters with a battery-powered visual device that can implement image processing algorithms and transmit measurements and alarms to a gateway.

2. Small leakage detection algorithms

In scientific literature, two different approaches to small leakage detection have been emerging: either centralized or distributed. As for the former, Ismail et al. [16] propose a prediction method based on consensus, while some methods based on pattern recognition algorithms are proposed to the aim in [17]. As for the latter, Alarefi and Walker [18], propose a shunt-like measurement to detect micro-leakage by using distributed flow measurements. In each of these proposals, leakage detection algorithms cannot be set up before a big data analysis on water

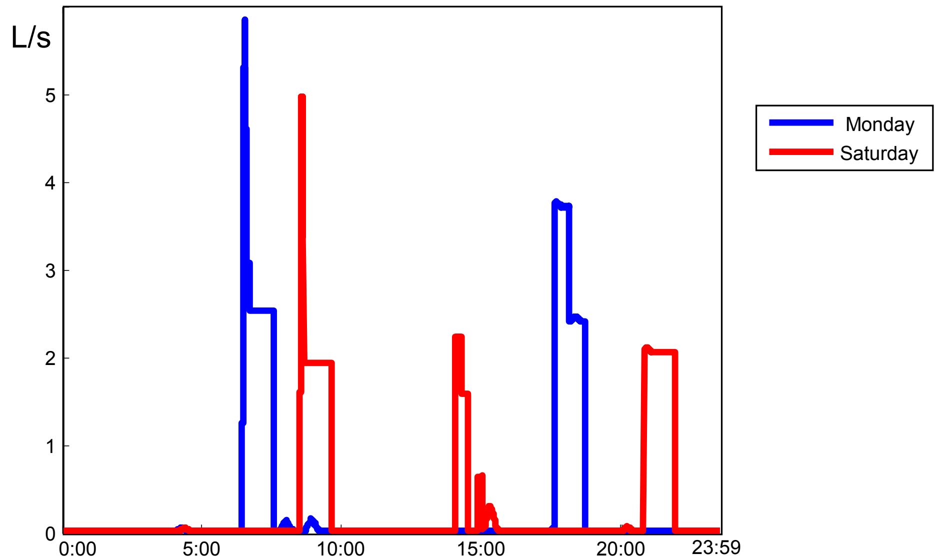

Fig. 2. Daily flow rate monitoring for two days of the week.

consumption in households that allows detecting habits. Consumer habits may change from a country to another; nevertheless, some mutual characteristics can be found in their daily or seasonal load curves [19–21]. These curves are usually reported in terms of either cumulative consumption or flow rate measurements. Water load curves are defined as cumulative consumption curves usually either over a day (more frequently) or over a week, but they could be traced over any other period of time.

As for an example, if:

- $y(t_i)$ [L] is the reading at t_i time of a water meter;
- $T_s=(t_{i+1}-t_i)$ = sampling time = 60 s = 1 min;
- observation time = 24 h = 1440 min;

the daily water load curve Z is defined as: $z(i) = (y(t_i) - y(t_0))$ for $i = 0$ to $i = 1440$, where i represents the considered instant.

In Fig. 1, the daily load curves of several days in the week are reported. Starting from 0:00 to 23:59, the curves look like a three-zone curve, but only two zones are significant: night (zone 1) and day (zone 2). Zone 1 starts with the last hours of the day, ends early in the morning, and is usually characterized by a null value. While zone 2 extends from morning to evening and shows a variable ascending trend due to daily water consumption, represented by edges [8].

Another way of representing daily water consumption is in Fig. 2, where the flow rate [L/s] versus time is reported for a 24 h time interval. Peaks are generated by fast consumptions, while offtake stops give zeros. In leakage detection algorithms, the last representation form can be easier to use than the former because it clearly highlights “periods with null consumption”.

Differences among days, months, and seasons arise in both representation forms. This fact means that no reference curve can be defined to generate residuals allowing water leakage to be detected. For example, during the night (zone 1 in Fig. 1), the water flow should be constant and close to zero. In particular, the average value of flow [L/s] within the time window 2–4 a.m. (when most utilizer have been filled, and users are asleep) can be defined as Minimum Night Flow (MNF). The nightly constant water flow generated by background leaks due to faucets and toilets could be detected through a comparison of the nightly consumption with MNF. It means that only after the evaluation of the nominal MNF of a single user, the detection of leakage can be made this way. To avoid both missed detection and false alarms, the MNF value should result from processing a large amount of data concerning the consumer.

A more convincing alternative could be found in estimating some objective characteristics of curves that should be quite invariant during seasons and wholly independent of consumers. For example, the Continuous Offtake [7] and the Period With Null Consumption (PWNC) are time interval values characterized by non-zero value and null value of measured flow [L/s], respectively, and both represent water absorption phases that are common to most contexts [19]. If a flow meter [L/s] is used, their evaluation is easier than in the case of water volume [L] measurements. Continuous offtake in the absence of leakage may only last for a limited time interval (a threshold). If it overcomes this threshold, water leakage can be detected. The threshold to be effective must be different between day and night. Since during daily hours maximum offtake takes place, the night threshold is always lower since no significant long-term offtake is expected during nightly hours. Otherwise, if there is no leakage after the meter, a certain number of PWNC should appear each day or in a lower time interval (a threshold). Continuous monitoring and comparison of these parameters with adequate thresholds could lead to leakage detection. In this case, thresholds would depend on the day and night phase only. This fact makes easy the implementation of leakage detection algorithms both on the smart meter and in a central unit. In any case, whatever the approach could be, two factors play a fundamental role in this challenge: (a) the minimum value of flow rate that is still able to determine a change in the water meter output; (b) the promptness of the continuous monitoring of the water meter output. Factor (a) is the water meter sensitivity and depends on the type of water meter. Factor (b) depends on the system adopted for the continuous automatic acquisition of the meter output. In the following paragraphs, these two factors will be treated in detail.

3. The sensitivity of domestic water meters

3.1. The domestic water meters

Three water meters, all compliant with Directive 2014/32/EU (Annex MI-001), were chosen to experimentally test the real sensitivity to minimal flow rates: two mechanical water meters and a digital flow-through ultrasonic meter. The first water meter is a five digits resolution dry dial multijet water meter, while the second is an eight digits resolution dry dial volumetric rotary piston water meter. Their metrological characteristics are fully described on their manufacturer (Maddalena) datasheet.

The ultrasonic sensor is conditioned by a digital circuit that continuously (not faster than 1 Hz) provides the flow rate [L/h] values. A

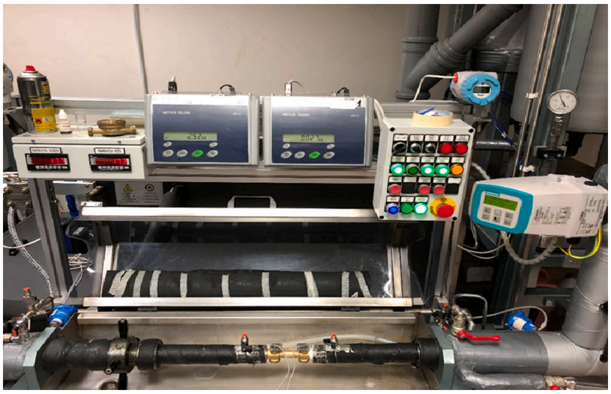

Fig. 3. The characterization station of the "LAMI" Laboratory.

microcontroller-based interface downloads measurement data via serial port at 4800 bit/s. An internal electronic accumulator provides the total amount of m^3 of water from the last reset.

The metrological characteristics [22] of the ultrasonic meter were obtained by a characterization procedure, carried out at the "LAMI" Laboratory of the University of "Cassino and southern Lazio", where the ultrasonic sensor was included in a loop together with a constant flow rate generator (see Fig. 3). The rig of LAMI Laboratory allows 2% stability in flow rate generation and 0.5% accuracy in flow rate measurement. The experimental results of the characterization are reported in Fig. 4 and are fully compliant with EU Directives.

The characteristics of the three meters, in accordance with Directive 2014/32/EU, are summarized in Table 1 where:

- Q_1 represents the lowest flow rate until which the threshold of 5% error is not exceeded;
- Q_2 is the transition flow rate namely the flow rate value which is between the permanent flow and the minimum flow;
- Q_3 the permanent duty, namely the highest flowrate at which the water meter can function satisfactorily in standard conditions;
- Q_4 is the overload flow rate at which the meter can operate satisfactorily for a short period of time without deteriorating

Analyzing the results, it is evident that the most significant differences among the meters are in the Q_1 and Q_2 values: the volumetric rotary piston sensor looks like being more sensitive and accurate at low flow rates and is characterized by a higher value of Q_4, thus showing to be more robust at very high flow rates.

3.2. The automatic acquisition of consumption

As aforementioned, most of small leakage detection algorithms aim to detect the period when the flow rate goes down to zero (see PWNC and MNF). In practice, "the zero value" will be equal to the sensitivity of meters.

Based on Directive 2014/32/EU metrological characterization, the lowest limit of their measurement sensitivity, defined as a threshold TH, intended as the minimum value of flow rate that is still able to determine a change in the meter output, cannot be directly deduced.

To the aim of determining the TH value, the meters considered were included in the same loop together with a calibrated constant flow generator. Concerning the ultrasonic flow meter, the TH value was reached by reducing the continuous flow rate until the electronic circuit provided no more measurement on the output serial port. A TH value of 3.6 L/h was the result of these tests. This performance has been very good for a cheap water meter thought for the household level.

As for the two water meters, since they measure water volume (m^3) and do not measure flow rate (L/h), a suitable test procedure was set up.

Let φ (t) be the instantaneous flow rate then, the total amount of water consumption in a generic time interval [t_m, t_n], Δ_{nm}, will be

$$\Delta_{nm} = \int_{t_m}^{t_n} \varphi(\tau)d\tau = \overline{\varphi_{nm}} \cdot (t_n - t_m) \tag{1}$$

where $\overline{\varphi_{nm}}$ is the average flow rate in the considered time interval. As a consequence:

$$\overline{\varphi_{mn}} = \frac{\Delta_{nm}}{t_n - t_m} = \frac{\Delta_{n0} - \Delta_{m0}}{t_n - t_m} \tag{2}$$

where $\Delta_{n0} and \Delta_{m0}$ are the total water consumption respectively at instants t_n and t_m.

This fact means that, in the common use of water meters, TH will be the average flow rate that causes the minimum Δ_{nm} detectable by eye. In other words, TH value can be defined as the maximum flow rate that does not generate any rotation of the less significant display rotating needle or digit.

A test campaign has been necessary in order to characterize the

Table 1
Hydraulic performance of water meters.

METER	Size [inch]	Q_1 [L/h]	Q_2 [L/h]	Q_3 [L/h]	Q_4 [L/h]
Multi-jet	½"	15.6	25	2500	3130
Ultrasonic	½"	10	16	2500	3000
Volumetric rotary piston	½"	6.2	20	2500	3200

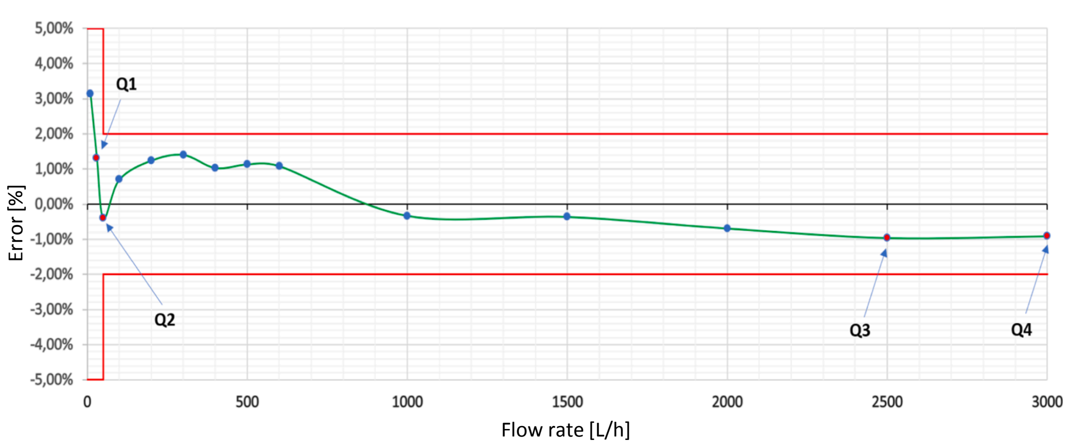

Fig. 4. Experimental results of the ultrasonic sensor hydraulic characterization. The red lines represent the maximum tolerated relative error.

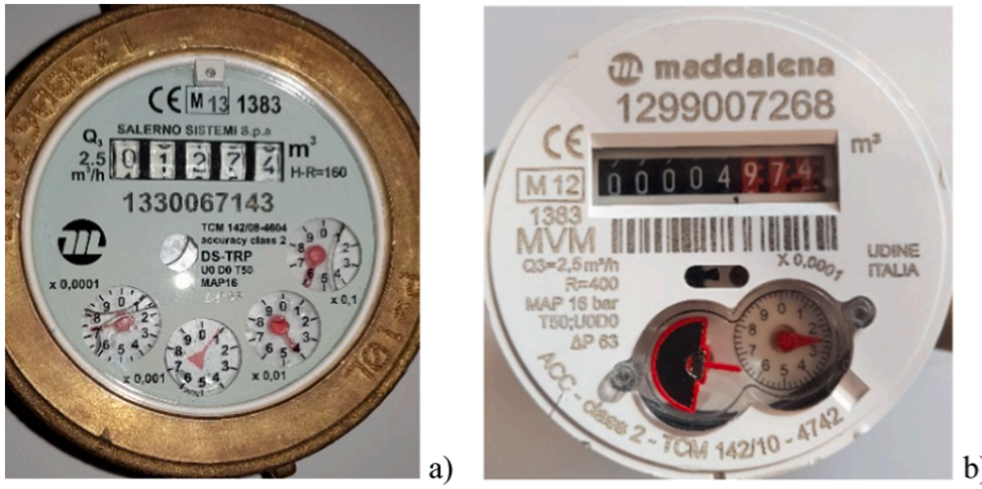

Fig. 5. The analyzed meters (a) multijet and (b) volumetric rotary piston.

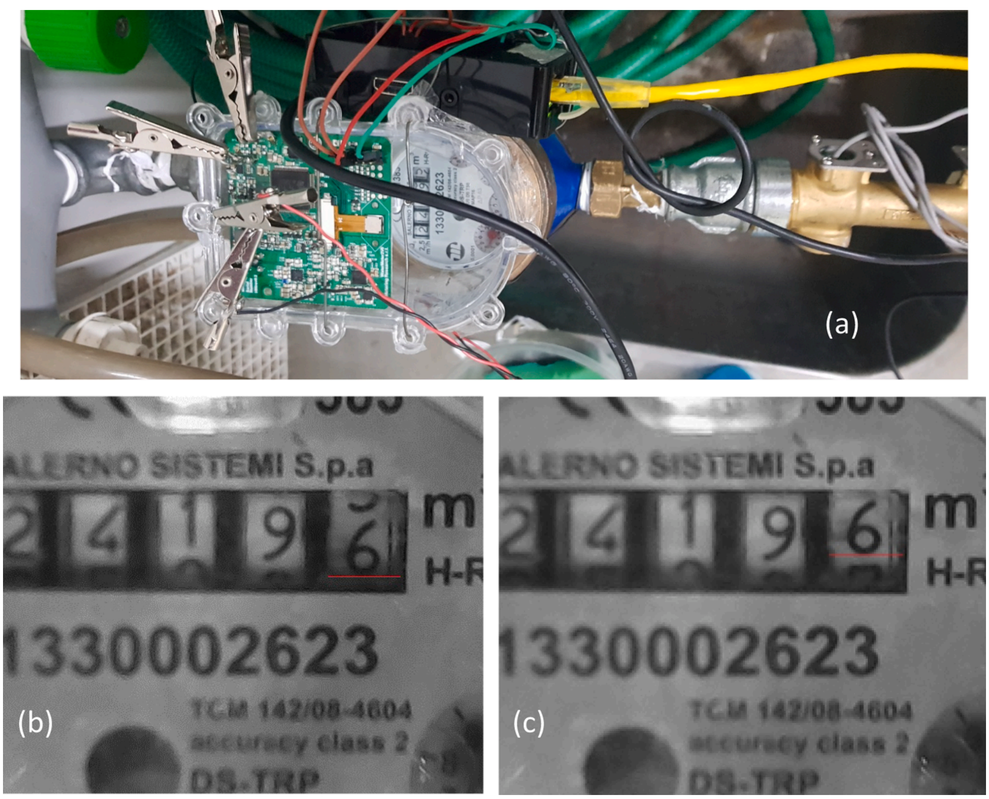

Fig. 6. TH evaluation for the multijet meter, (a) the connection of the meters to the characterization station, (b) acquired image at the start of test (c) acquired image at the end of the test.

detecting rotations capability due to flows equal to or higher than the TH of meters. At first, rotation detection was made by the human eye. A constant flow was generated with decreasing rate steps until any rotation of the last needle (see Fig. 5) of the counter could be detected. The multijet meter has been resulted sensitive to flow rates higher than 7.8 L/h. The same evaluation, done for the volumetric rotary piston water meter, has provided a TH of 2.8 L/h.

To pursue the aim described above, a suitable electronic add-on device designed to acquire images of water meters' display, was mounted on classical water meters.

The electronic device is featured with a suitable battery powered microcontroller named STM32F407VGT6 by STMicroelectronics [23], responsible for managing a 640x480 resolution camera, and it is applied to the water meter utilizing a suitable case compliant with the glass displays of the meters (Fig. 6a). The camera module employed is the OV7670 based on a CMOS image sensor that provides all the full functionality of a single-chip VGA camera and image processor in a tiny footprint package. The OV7670 is controlled through a Serial Camera Control Bus (SCCB) interface, while the images are transferred to the microcontroller unit using the Digital Camera Interface (DCMI) bus. The add-on device is also provided with several serial digital ports to send out the raw acquired pictures and communicate with any smart water meter. There are several analog inputs to acquire also analog signals. Results showed in the paper were obtained in off-line processing by Matlab MathWorks 2019a, but the same algorithm is going to be implemented in the add-on processor to be real-time executed.

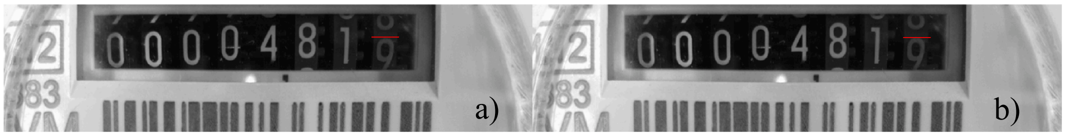

Fig. 7. TH evaluation for the volumetric rotary piston meter, (a) acquired image at the start of the test, and (b) acquired image at the end of the test.

As previously defined, the TH value will correspond to the flow rate that determines the minimum detectable position change of the last digit (or the needle). Using the add-on presented and an image processing algorithm, the TH corresponds to the flow rate that causes the minimum detectable change in the digital image, which corresponds to the vertical or horizontal resolution (row or column) within a sampling period. Then, the same approach, used in manual detection, was followed and implemented in the camera-based embedded system. In particular, for each meter, an image is acquired, and a Region of Interest (ROI), is defined; at each sampling period, a new image is acquired and processed in the ROI in order to detect significant changes.

Several solutions were experienced, based on the observation of different meter's dial region (Region of Interest, ROI): (i) the rotation of the slowest digit; (ii) the angular variation of the needle's indicator of interest.

The two number dials of the water meters have different resolutions: 1 m^3 resolution (Least Significant Digit LSD) for the multijet (Fig. 5a) and 0.001 $\mathbf{m^3}$ LSD for the volumetric (Fig. 5b). As for the needles, the less significant decade is 0,0001 m^3 for both. The first tests were made on the LSD of the multijet. As the expected TH value was about 7 L/h, a 1 h frame rate period was chosen. This fact means that in a 24-hour test, 24 consecutive images of the ROI were taken to estimate the different positions of the digit between two of them. Fixing a reference pixel's row, chosen in correspondence of the current least significative digit displayed on the display's meter, the minimum position change of the selected horizontal pixels' row corresponds to one pixels' row in one hour resulting in a moving of the 24 rows in 24 h whit the sampling period adopted. The experiment was repeated more than once, every time with a decreasing constant flow rate value. Following this approach, a TH corresponding to a flow rate of 7.8 L/h was measured; in Fig. 6 are reported two images acquired at a temporal distance of 24 h (see red line in Fig. 6b and c). This result complies with what was expected: considering the camera and the focus used, each least significative digit (corresponding to 1 m^3–1000 L) has needed 128 pixels' rows of the camera field of view to be scrolled. This fact matches the flow rate previously estimated at 7.8 L/h. It has to be noted that, at so slow flow rate, the human eye has not been able to detect a minimum rotation of the LSD before 24 h. This let understand that human eye would not have any chance in trying to detect the rotation at the minimum flow rate, as an example, after just a few dozens of minutes.

In the case of volumetric rotary piston meter, the least significant digit has 0.001 m^3 resolution, which is much lower than the previously analyzed case study regarding the multijet water meter (1 m^3 resolution). For this reason, the minimum sampling period (due to the used hardware) equal to 6 s was adopted, and consequently, a smaller observation time window of only 60 s was chosen. Also, in this case, some series of 60 s windows were carried out at descending constant flow rate values. In this case, the minimum detectable change in the ROI was one row every 18 s. More specifically, one row corresponds to 0.014 L since the whole 0.001 m^3 digit covers 71 rows (see Fig. 7). The resulting flow rate considering that 0.014 L of water flowed in 18 s was 2.8 L/h, which is a value fully compliant with the TH value observed by eye. This is an expected result because the TH cannot depend on the detection technique but only by the water meter. On the contrary, the promptness of detection definitely improves from dozens of hours to dozens of seconds.

In order to further improve this value of detection promptness, additional tests were made on the dial needles. In this case, circular ROIs were considered, as reported in Fig. 8, where a red circle highlights the ROIs, and the angular rotation of the needles were monitored by the electronic add-on.

Based on both the camera resolution and the relative weight of the needle indicator respect to the whole ROI, not more than 200 different positions can be resolved, consequently the minimum detectable angle variation was equal to $360^\circ/200 = 1.8^\circ$. This angle resolution corresponds, respectively, to 0.05 L for the multijet and 0.005 L for the volumetric meter.

New tests were made again with constant flow rates and using the minimum sampling period. A flow rate equal to the TH value (2,8L/h) was detected in 1 frame from the volumetric meter, which means in 6 s. On the other hand, 6 frames need to be acquired before detecting a rotation equal to the resolution of the multijet needle (0,05 L) for a flow rate equal to its TH value (7,8 L/h), while flow rates higher than 30 L/h can be detected in only 6 s. To verify the proposed approach, two constant flows have been generated: 30.0 L/h for the multijet and 3.0 L/h for the volumetric. The acquisition system has been set to take a needle picture every 6 s and considering an observation window of 30 s for both the meters. The angle variation between two consecutive frames was 1.8° (see Fig. 9), which, considering the sampling period adopted, it corresponds to a flow of 30,0 L/h for the multijet and 3.0 L/h for the volumetric, which are precisely the constant flows applied for the tests. As a further result, in Fig. 9, the linear behavior for both needles' water

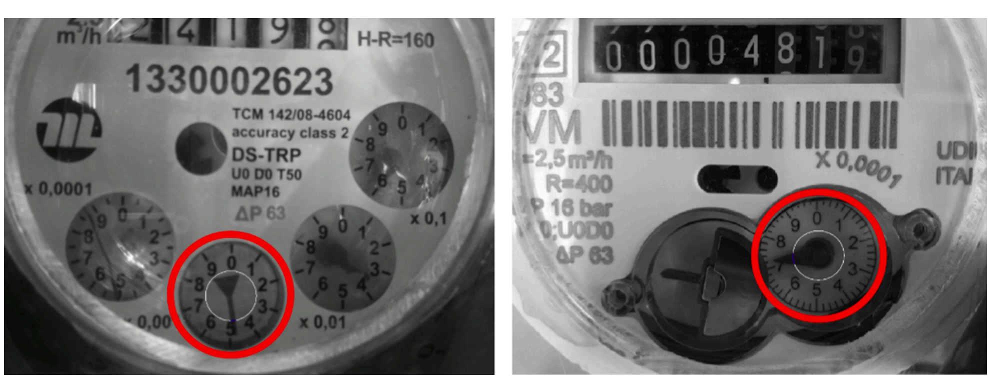

Fig. 8. Needles highlighted in red with the circumference locus of points in white and intersection with the indicator in blue. (a) multijet water meter, and (b) volumetric rotary piston water meter.

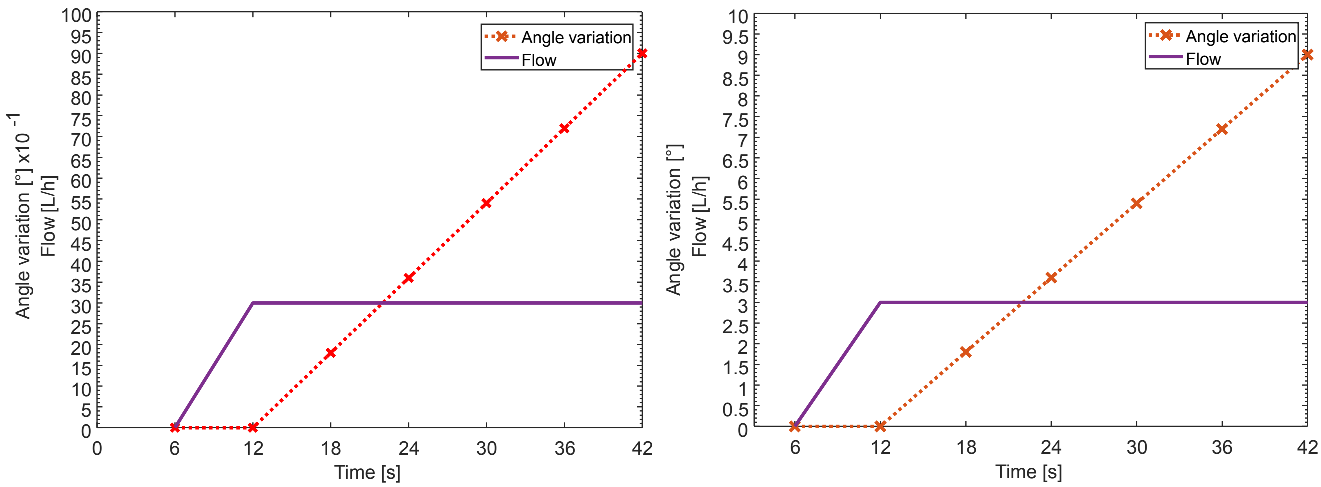

Fig. 9. Angle variation in red, with flow profile in blue. (a) multijet water meter, and (b) volumetric rotary piston water meter.

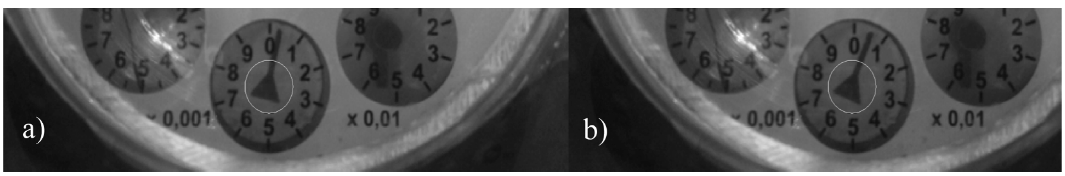

Fig. 10. Acquired image at the start of the test (a) and the end of test (b) for the multijet water meter.

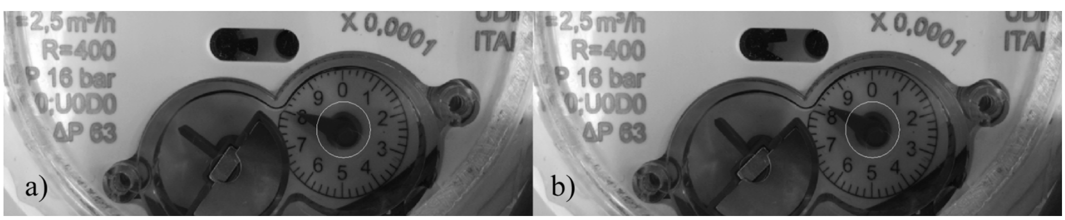

Fig. 11. Acquired image at the start of the test (a) and the end of test (b) for the volumetric rotary piston water meter.

meters can be appreciated for the small flowrate applied; this last result is very interesting since both the meters are operating near their starting flowrate TH.

In Figs. 10, and 11, the pictures at the beginning and the end of the tests for both the meters are reported. It is easy to detect by eyes the changes in the position of the indicator, which have been of 9° according to the expectations.

In the conclusion of the tests, we can say that all meters could be used for detecting low flow rates even if with different sensitivity and response time, provided they are featured with an electronic device to send a numeric evaluation of the flow rate. Besides, the time response also indicates the minimum time interval of null consumption that the meter is capable of detecting.

4. Concluding remarks

Water leakage detection at the household level has become today an objective that can no longer be postponed. To this aim, all the known detection techniques require a continuous stream of high-resolution measurements. These requirements are not fully satisfied by most of the domestic smart meters, because of both the scarce resolution of the water meters and the limited autonomy of the battery-powered electronics. The metrological performance characterization of three water meters that could be embedded in domestic smart water meters exhibited a sensitivity value (TH) that could be useful to detect leakages not lower than 4 L/h for the ultrasonic, 7,8 L/h for the multijet and 2,8 L/h for the volumetric. The proposed electronic system has been designed to acquire and process: (i) camera pictures, (ii) serial digital output of any water meters; (iii) analog signals. Future researches will be directed towards the development of an innovative onboard leakage detection algorithm and its application to a real testbed.

CRediT authorship contribution statement

Marco Carratù: Formal analysis, Writing - original draft, Writing - review & editing. **Consolatina Liguori:** Formal analysis, Writing - original draft, Writing - review & editing. **Antonio Pietrosanto:** Formal analysis, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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