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Household flow detection using FEAT (flow estimating accelerometer-thermometer) device

Paul Wills [a,*], Fayyaz Ali Memon [a], Yulei Wu [b], Paul Merchant [c], Malcolm Roberts [c]

[a] *Centre for Water Systems, University of Exeter, Stocker Road, Exeter, Devon, United Kingdom*
[b] *Department of Computer Science, University of Exeter, Stocker Road, Exeter, Devon, United Kingdom*
[c] *South West Water, Rydon Lane, Exeter, Devon, United Kingdom*

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ABSTRACT

The use of IoT devices in water end use disaggregation verification is an emerging field which offers benefits over conventional approaches, in terms of cost, accuracy and scalability. Having reliably disaggregated water appliance consumption data will enable smart water meter data to be used in household water conservation approaches and for understanding water consumption behaviours. The FEAT device provides a low cost, easily applied and scalable solution that is demonstrated to work even for very low flow conditions of 0.03 l/s. The FEAT device is a combination of a battery, Wi-fi board and MPU6050 sensors providing multi-modal accelerometer and thermometer data. The study places 7 of these FEAT devices onto hot and cold water pipes leading to a shower, which is operated 4 times in a high flow situation, 0.13 l/s, and 4 times in a low flow situation, 0.03 l/s. The data is then analysed and compared with a flow logger to determine if the FEAT device can detect when a domestic appliance is using water. There are limiting cases where the level of noise or external interference limits distorts the data, obscuring the distinguishable peaks in the data due to the similarity of the values. By using high and low pass filtering methods it was possible to enhance the peaks but there are still situations where peaks cannot be detected: for example, if a rigid pipe is not able to vibrate easily or if a hot water boiler is not triggered due to the low flow rate. However, the results show it should be possible to overcome these limiting cases, as it is much less likely for both the vibration and temperature data to be adversely affected by noise or external influences simultaneously, therefore decreasing the effect of noise and external influences. In conclusion, this research paper demonstrates that FEAT devices are a low cost, easily applied and scalable solution for detecting flow. By using high and low pass filtering, placing sensors on freely moving pipes and through the use of multimodal verification, the FEAT device is shown to work on both metal and plastic pipes even in the lowest flow situations of 0.03 l/s. Therefore the FEAT device is a suitable solution for appliance identification in disaggregation verification datasets.

1. Introduction

The ever-increasing issue of water stress/scarcity is due to climate change, growing populations, and urbanisation. To mitigate the water stress, conservation methods can be employed, making efficient use of water. For specifically targeting residential consumption, understanding how people use water is significant in creating customised solutions for individual households and to target behaviour patterns, [1]. To estimate customer water usage habits, there are two main methods: surveys or disaggregation (micro-component analysis). Disaggregation is preferred for understanding domestic consumption as it utilises flow measurements, [2,3]; surveys are time-consuming and inaccurate by using estimates from a householder, [4].

Disaggregation is based on measuring actual flow consumption on a smart meter/logger, breaking the usage into micro-component parts (shower, tap, etc). There are various methods for which disaggregation can be performed but creating a reliable model requires a robust ground-truth dataset. To know definitively the water usage at any one time, a measurement needs to be taken on the pipe leading to an appliance. This paper presents the FEAT (Flow Estimating Accelerometer-Thermometer) device development and its testing. FEAT is a small, low-cost, non-intrusive (attaches outside the pipes) tool, suitable for the purpose of

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* Corresponding author.
E-mail address: pw375@exeter.ac.uk (P. Wills).

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flow detection. This study tests the FEAT device in a methodical way within a laboratory-type environment with the aim of determining the factors that could affect the result of any flow measurement in real world conditions, thereby increasing the success of any future field testing.

2. Previous approaches

Traditional approaches for creating disaggregation verification datasets have revolved around either:

- keeping a water diary/surveys (inaccurate and time consuming) [4–6],
- manual identification of a flow trace (requires human judgement and is labour intensive) [7,8],
- using an expensive flow-switch for determining appliance usage [9],
- have an expensive, moderately intrusive device to measure the pressure combined with a time-consuming calibration period [10],

The way to overcome the limitations of the aforementioned approaches is to have low-cost, non-intrusive automated sensors on each appliance that can detect when flow is occurring. The need for low-cost sensors for use in water use behaviour understanding and management was first demonstrated in the "UpStream" project, [11]; with technology advancements providing the foundation for combining sensors and data analytics to understand consumer behaviour [12] used a magnetic sensor attached to the flow meter and accelerometers onto the water inlet pipe and the outlet pipe of a water heater. The accelerometer data generates features at different frequencies, creating clusters for disaggregating the water uses. Using two accelerometers [12], were able to have a 90% accuracy for the disaggregation. The experiment in this paper will demonstrate FEAT sensing devices that can be applied to the inlet pipe of individual appliances, determining precisely when water is flowing, allowing the creation of a ground truth dataset with pre-identified appliances, that can be used as part of a model for identifying appliances on extrapolated datasets in any future household water disaggregation studies.

2.1. Flow measurement

The application of using flow measurement devices at an individual appliance level for the purpose of disaggregation in homes is an emerging field. The main limiting factors are due to hardware costs and residential internet speeds, both of which have improved dramatically over the last decade due to the rise of Arduino based computing boards and better wi-fi and fibreoptic technologies respectively. Microelectronic measurement sensors have widely been used in leak detection, [33], but less so for flow measurement; with flow measurement being more closely aligned to flow detection, since flow measurement and flow detection both use the flow rather than leak detection which uses pressure.

A review of sensing methods in, [13]; explains that vibration sensors are the lowest cost solution with high sensitivity, and also suggests that "The best sensors can measure three axes because the plastic pipeline moves in three dimensions when the water flow is accelerated in the pipeline". The study goes onto to explain that the only sensor which measures all three axes with a high accuracy, low purchase cost and low power consumption is the MPU6050. The MPU6050 inertial measurement unit (IMU) has a temperature sensor in addition to the three accelerometers, which is useful since accelerometer performance can be affected by the operating temperature, [32]. The FEAT method proposes a new approach, using the MPU6050 to measure the temperature of the water and the vibration, removing false positives through the comparison of external influences on the data results.

2.1.1. Vibration

The principle behind the measurement of flow using accelerometers is explained in [14]; where turbulent flow generates the vibration; the amount of turbulence varies with the pipe size, pipe material, and pipe topography. Provided that the inlet pipe diameter is less than 2.5 cm, the minimum expected flow rate for appliances in the home will exceed the critical flow rate needed for turbulence and therefore pipe vibration will be detectable and can therefore be used to identify appliance water consumption. The following notable studies have used vibration in flow measurement:

- [15] – proposed the use of accelerometers to measure flow using three accelerometers using an excitor to provide additional vibration, giving a value that was on average 12% higher or lower than the actual flow rate.
- [16] – demonstrated how signal noise as standard deviation correlates with flow rate.
- [17] – used machine learning to calibrate single accelerometers for measuring the flow rate based on the vibration.
- [18] – showed that by isolating certain peak frequency amplitudes, the linear relationship between pipe flow and pipe acceleration can be proven experimentally.
- [19] – increased the accuracy of the relationship between pipe flow and pipe acceleration using "wavelet denoising", with a R-squared of 0.999 for the peak amplitude against flow rate.
- [20] – used large piezoelectric sensors and accelerometers to measure flow non-invasively on straight pipes and pipe bends. The study found that sensors applied to bends exhibit a stronger reading for measuring flow rate, with piezoelectric having a marginally closer correlation.

2.1.2. Temperature

As described in [14]; vibration measurements in pipes can become complicated due to other sources of vibration: cavitation in pipes due to the collapse of vapour bubbles and extraneous vibration due to footfall and exhaust fans (e.g. in a shower). To improve the accuracy of determining if vibration detected is from water flowing through the inlet pipe of the appliance, this study proposes to use a temperature sensor in conjunction with the accelerometer. Water flowing from other parts of the house/outside the property should have a different temperature to that of the water that begins next to the appliance and hot water pipes will have heated water that will increase in temperature.

Previous studies that have measured flow using temperature have either involved using an additional heat source, or only measure flow for a single appliance:

- [21] – correlated flow and temperature measurement with a thermometer directly behind a heat source inside of the pipe.
- [22] – used temperature measurements to determine shower consumption.
- [23] – determined garden irrigation usage based on temperature differences.
- [24] – a non-invasive heater and downstream sensor are clamped onto the pipe and show a correlation between volume flowrate and fluid temperature.

2.2. Flow detection

Since the flow event detection method uses an accelerometer and a thermometer, it can be described as a multimodal (multiple sensors) approach. This was defined in [25] critiquing studies that implemented flow meters in conjunction with either an accelerometer, infrared sensor or a radio-frequency identification chip.

The experiment in this study takes the multimodal (multiple sensors) approach a stage further by examining the viability for disaggregation verification, with the flow meter outside the property and the FEAT device attached to appliances within the property. Using an accelerometer measuring vibration and a thermometer measuring temperature, it is proposed that combining the two sensors will help to rule out any false positives and therefore increase the accuracy of appliance identification. The only known studies that use multiple sensors in relation to flow detection are:

- [26] – combined an accelerometer and a thermometer to detect water usage events on an electric water heater.
- [27] – Used a piezoelectric vibration sensor to detect and measure flow and recorded the temperature only at the end of each event

None of these studies used vibration and temperature in a multimodal (multiple sensors) approach for household disaggregation verification and it is this application which is novel and explored in this paper. For identification of water appliance water usage, the devices only need to give a binary response, i.e. if an appliance is being used or not and when compared with the flow, trace allows for consumption characterisation. For combined events, a further model will need to be created, based on typical consumption events for each appliance (as detailed in Section 4.4). The goal is to show that these small, low-cost, non-intrusive FEAT devices are viable as a tool for the verification of the disaggregated flow, with the combination of an accelerometer and a thermometer as a method for increased accuracy.

3. Methodology

3.1. FEAT device assembly

The FEAT device (Fig. 1) is comprised of three readily available components: MPU6050 Inertial Measurement Unit (Containing acceleration and temperature sensors); ESP8266 Wi-fi control board (LoRaWAN Compatible); and 26,800 MaH battery with USB connection.

The MPU6050 is a sensor board with a gyro, thermometer and accelerometer and is connected to the ESP8266 control board which has wi-fi capabilities and is powered via USB using a 26,800 MaH battery. The battery powered ESP8266 is coded in Arduino and takes readings from the MPU6050, which then comprises the FEAT device. Data is sent using wi-fi on the ESP8266 control board part of the FEAT device; the data travels via a router to a cloud data storage server.

3.2. Experimental setup

In this study, multiple FEAT devices are attached to pipes that lead to a shower, to record flow, temperature and vibration readings resulting from the flow within the pipes. The readings are then compared for variation in:

- pipe material (copper, PVC and Nylon);
- geometry (straight, curved and joints); and
- pipe fixing (cemented to wall, hanging loosely).

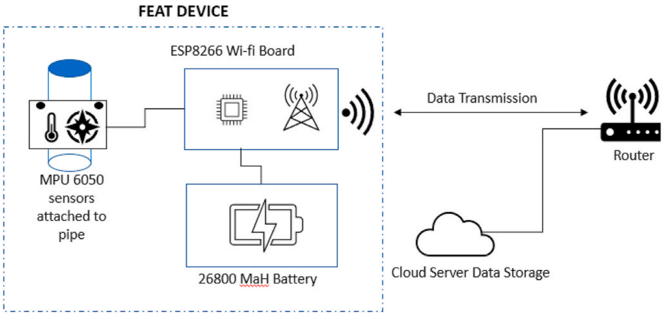

Fig. 1. FEAT device composed of MPU6050 sensors, ESP8266 Wi-fi Board and a 26,800 MaH Battery which transmits data via Wi-fi through the Router and stores the data in the cloud.

A number of repeat experiments were conducted for both hot and cold-water pipes in low (0.03 l/s) and high flow (0.13 l/s) scenarios.

The experiment consists of two types of devices: a flow logger placed onto the external water meter that will register flow events and FEAT devices placed on the pipes feeding water to an appliance (i.e. shower in this case), (Fig. 2). The characteristics for the data collection are shown in (Table 1). The FEAT devices were attached on seven different locations as described in (Table 2) and shown in (Figs. 2–4). Using the FEAT devices, it will be possible to identify which of the flow events can be attributed to the shower.

The experiment has simultaneous data collection from seven FEAT devices in different positions on pipes leading to the shower, synchronized with data collection from the flow logger.. The FEAT devices are placed in seven different locations with varying topological aspects to determine the pipe characteristics and locations that are conducive to creating sharp peaks in the graph data illustrated in (Fig. 2). For temperature, different pipe materials (Table 2) have distinct thermal conductivities, therefore Nylon, Copper and PVC are used during the experiment to compare the material performance in flow detection. For vibration, three factors affect the magnitude of the acceleration, the topology affects the amount of turbulence generated which is proportional to the vibration. The rigidity and fixing of the pipe affect how freely the pipe moves, i.e., a rigid pipe that fixes into the wall will be dampened.

The experiment to test the FEAT device was repeated 4 times in the full shower flow situation (0.13 l/s), and 4 times in the low shower flow situation (0.03 l/s) with a mix of both hot and cold water. The order of running for the experiments is shown in (Table 3), with shower runs lasting approximately 2 min 30 s. The flow rate was kept consistent using a protractor to measure the angle of the shower level and the flow rate measured on the logger that was external to the property. Additional experiments were conducted to determine the influence of the synchronous and sequential tap and toilet operation on the extent of vibration and temperature variation.

3.3. Data processing

3.3.1. Vibration

Due to the direction of turbulence varying within a pipe, an absolute composite value of the three planes of acceleration enhances the peaks, since noise is random and the acceleration values during flow should exceed the noise, adding together three values that exceed the noise will increase the magnitude of the readings relative to the noise (Figs. 5 and 6).

Vibration data was filtered using a high pass Butterworth filter to correct drift for the accelerometer data, as similarly used in [28]. There is significant noise in all three planes of acceleration (Fig. 5), smoothed using a rolling average, as used in [29]. The result of the filtering is shown in (Fig. 6).

3.3.2. Temperature

The temperature reading shows a strong effect (Fig. 7) but it is difficult to compare the performance of the materials simply by visual inspection of the temperature readings due to the starting values and maximum and minimum varying significantly. To make sure this is not a calibration issue, the FEAT devices were left to settle at the end of the experiment and the temperatures were all within 1.5° Celsius (Fig. 8), which is within the error range of the sensor, ± 1 Celcius, [30].

The differing locations of the pipes can also have localised temperature effects, to enhance the comparability of the temperature between the materials, a temperature differential (Figs. 9 and 10) can be calculated after reducing the noise using rolling averages, as used in [29].

4. Results

The results are divided into two sections for the vibration and

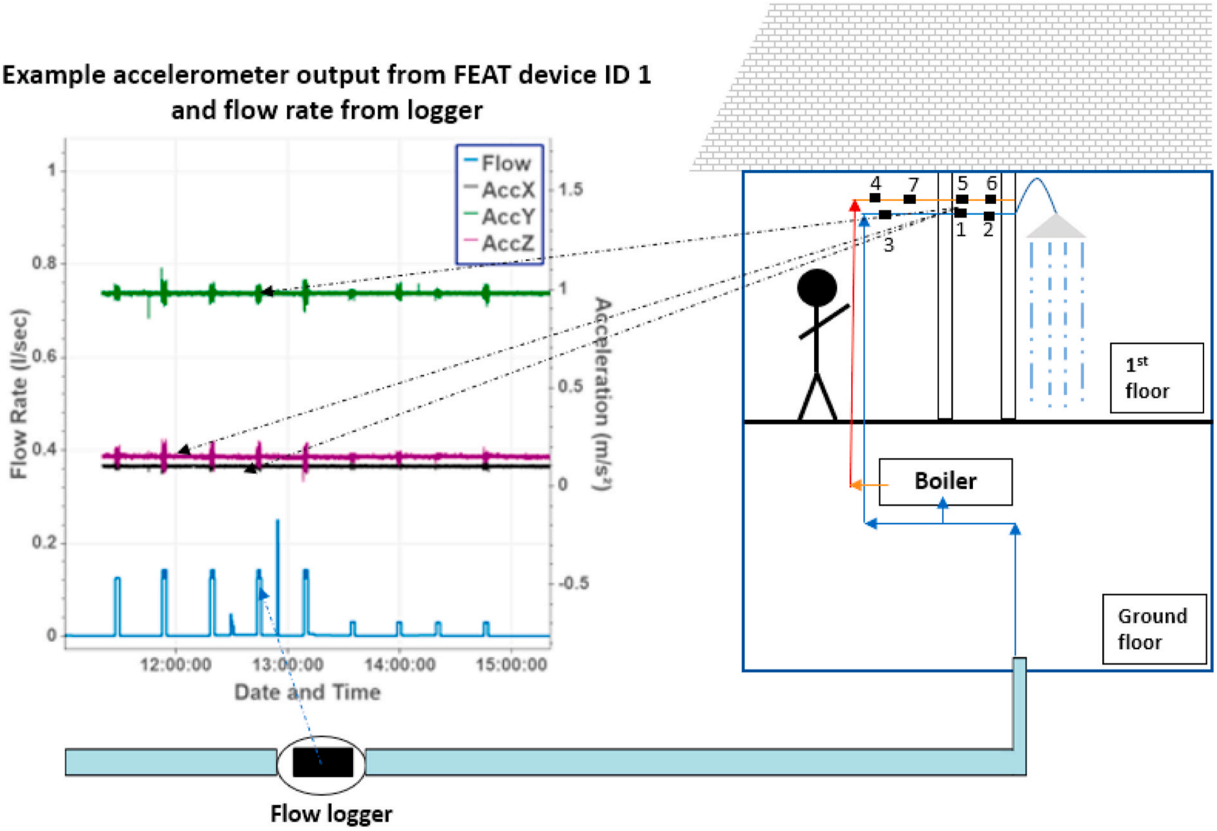

Fig. 2. Data collection from the flow logger and FEAT devices (IDs 1–7 as in Table 2 and Figs. 3 and 4) with a graph showing an example output for the flow logger and an example output from the Copper4 FEAT device. The acceleration is measured in three axes, X,Y and Z. AccX = Acceleration in X axis (black), AccY = Acceleration in Y axis (green), AccZ = Acceleration in Z axis (purple).

Table 1
Location, reading frequency and transmission frequency for the flow logger and FEAT device.

	Flow logger	FEAT devices (ID 1–7)
Device location	Attached to mains water meter on property boundary	Attached to hot and cold water pipes preceding the shower
Reading frequency	Records change in litres on the water meter every second	Measures temperature and acceleration of pipe every 0.6 s
Data transmission frequency	Every 24 h	Every 0.6 s

Table 2
Pipe Characteristics for testing the FEAT devices To detect the flow, the MPU6050 sensors on the FEAT devices were attached to the pipes using electrical tape, ensuring a consistent contact. The sensors of the FEAT devices were attached to the pipes at seven different locations (Figs. 3 and 4).

FEAT ID	Hot/ Cold Water	Pipe Material	Topological Data	Rigidity	Fixing
1	Cold	Nylon	Slight curve	Flexible	Loosely hanging
2	Cold	Copper	Straight near join	Rigid	Cemented into wall
3	Cold	Nylon	Curved	Flexible	Loosely hanging
4	Hot	Copper	Near T junction	Rigid	Adjoining another rigid pipe
5	Hot	Nylon	Slight curve	Flexible	Loosely hanging
6	Hot	Copper	Straight	Rigid	Cemented into wall
7	Hot	PVC	Bend	Rigid	Loosely hanging

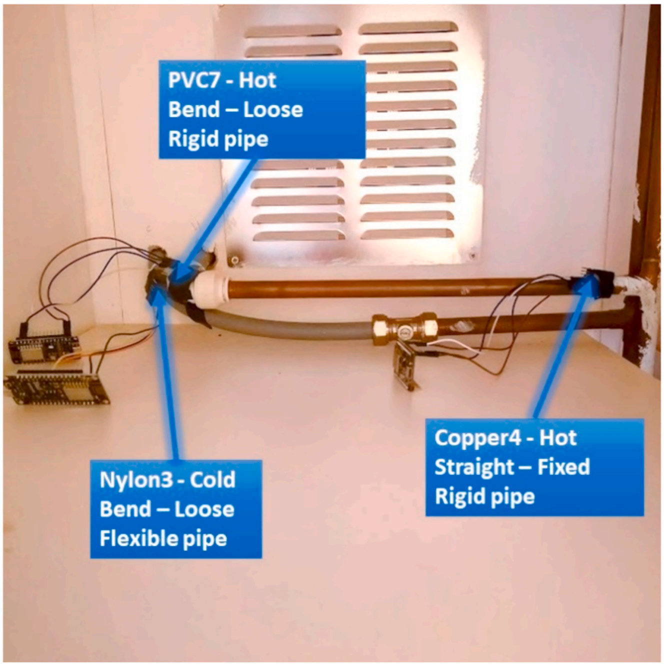

Fig. 3. FEAT devices ID 3, ID 4, ID 7.

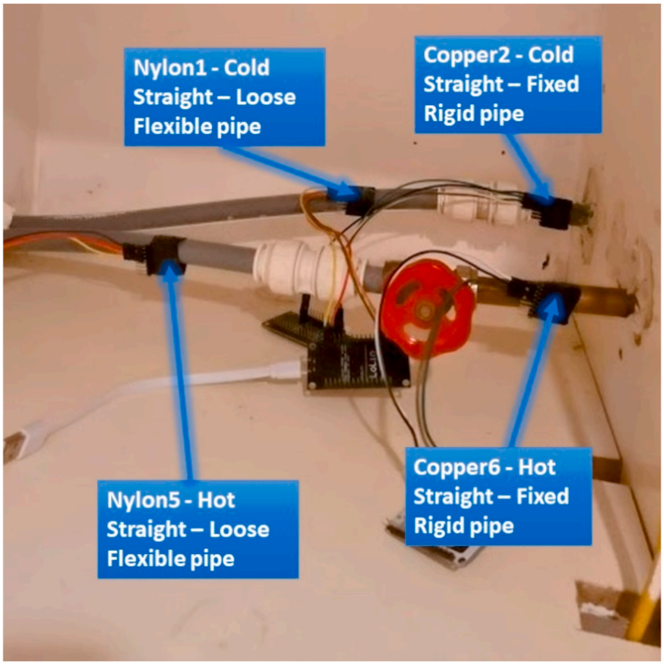

Fig. 4. FEAT devices ID 1, ID 2, ID 5, ID 6.

Table 3
The running order for the experiments with timings based on readings from flow logger.

Event Type	Event Start	Event Finish	Duration
Calibration/Preliminary test run	11:27:42	11:30:06	00:02:24
High flow shower run 1	11:52:48	11:55:13	00:02:25
High flow shower run 2	12:18:27	12:20:56	00:02:29
Tap test	12:29:34	12:31:12	00:01:38
High flow shower run 3	12:43:37	12:45:58	00:02:21
Toilet test (full flush)	12:54:33	12:55:03	00:00:30
High flow shower run 4	13:08:40	13:11:01	00:02:21
Low flow shower run 1	13:33:54	13:36:03	00:02:09
Low flow shower run 2	13:58:45	14:00:57	00:02:12
Low flow shower run 3	14:19:31	14:21:46	00:02:15
Low flow shower run 4	14:45:14	14:47:28	00:02:14
Toilet test (small flush)	15:25:31	15:25:35	00:00:04

temperature.

4.1. Temperature

The temperature differentials (Figs. 11 and 12) are almost identical for the same materials, with copper showing up to four times the amount of peak temperature change relative to plastic materials.

The difference in temperature differentials varies significantly depending upon the temperature and flow rate of the water in the pipe. At the peak values, the cold copper pipes have up to 400% higher temperature transfer than the cold plastic pipes, compared with only 80% higher temperature transfer in the hot copper pipes relative to the hot plastic pipes. This is notable since the range (Fig. 7) is lower for the cold than for the hot pipe, 22–28 vs 30–43° Celcius respectively.

For the differing flow rates, the cold-water readings are the only basis for comparison since the flow rate in the hot water pipes was too low to trigger the boiler into action. In the low flow (0.03 l/s) measurements, the difference between the materials for the temperature transfer was as low as 20%, compared to 400% in the high flow (0.13 l/s) measurements. This shows that both the temperature of the water and the flow rate influence the thermal transfer of pipe materials.

Given the thermal conductivity of pipe materials (Table 4), it would be expected that copper would have a higher temperature differential than plastic, but since the difference in the thermal conductivity is shown to be up to 286,429% (401/0.14*100)%, other factors must also affect the temperature transfer.

In the [31] study, a temperature range of 97–147 was measured, where it was found that “statistically there is no difference” between the piping materials, suggesting that “balance will occur when there is a constant heat and that the tubing walls are too thin to make a difference”. These findings suggest that there is potentially a maximum heat transfer threshold that affects both materials and the thermal conductivity only comes into effect below this threshold. However, it is beyond the scope of this paper to research the reasons behind this effect.

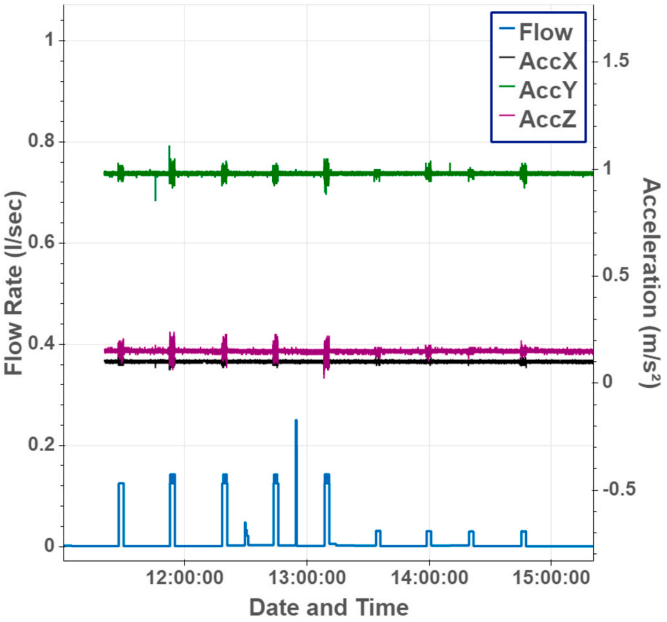

Fig. 5. Accelerometer readings for Nylon1 in three different planes, X in the direction of flow, Y for side to side movement and Z for up and down.

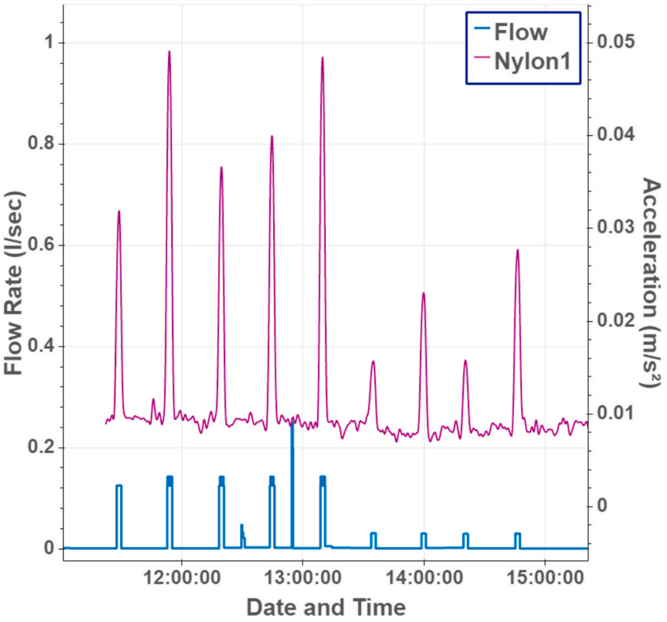

Fig. 6. Filtered absolute composite of the acceleration for Nylon 1, combining the X,Y and Z planes, with low and high pass filters to enhance peaks.

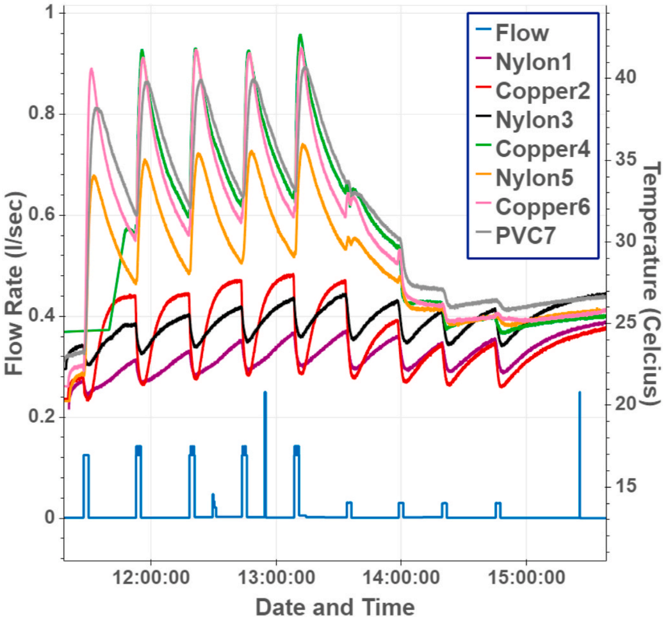

Fig. 7. Temperature readings.

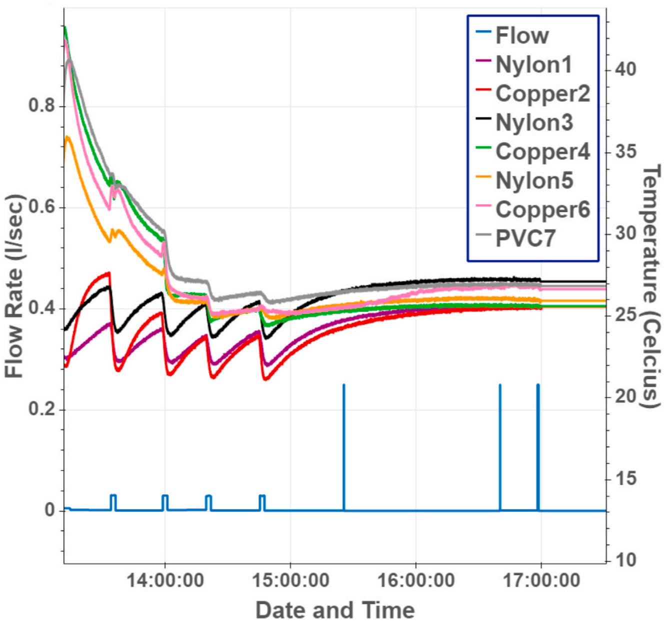

Fig. 8. Calibration temperature comparison.

4.1.1. Thresholding

To determine whether an event occurred, a dashed line threshold is applied to the temperature differential (Figs. 11 and 12). In the cold-water pipes, a threshold of −0.002 Celcius/Second is clearly sufficient to capture even the lowest flow events without any risk of false positives. However, the hot water pipes are more complicated due to low flow situations where the boiler may not be triggered into activation. A 0.002 Celcius threshold applied to the hot water captures the events when the hot water flows, but not when the boiler is doesn’t activate and cold water is flowing through the pipe. Though the flow rate is very low, it is still preferable to capture all the appliance usage for disaggregation purposes. This is where vibration is useful in a multimodal approach.

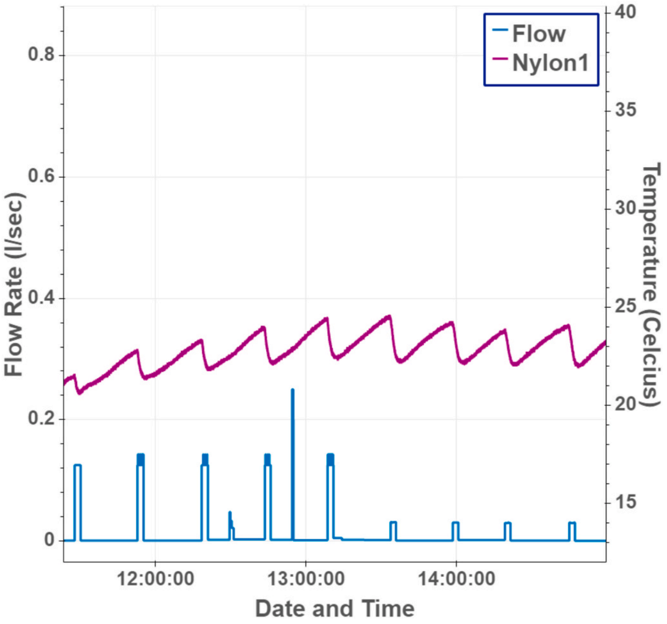

Fig. 9. Temperature readings for a single FEAT device, Nylon 1.

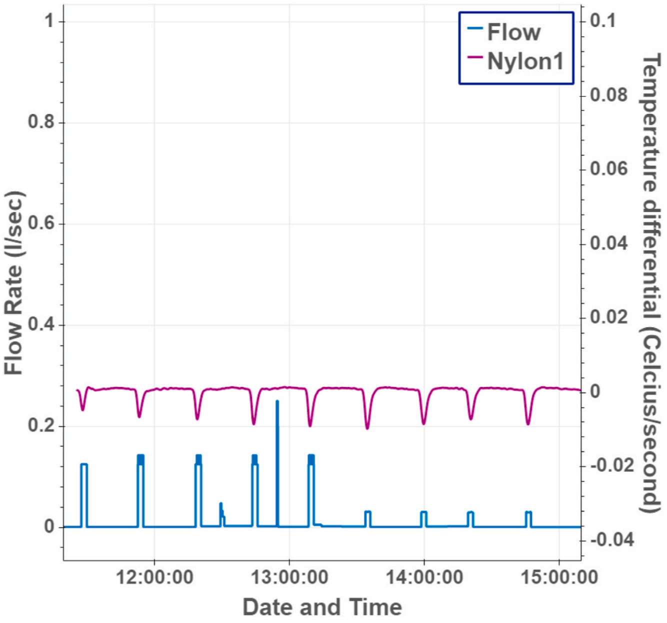

Fig. 10. Smoothed temperature differential for a single FEAT device, Nylon 1.

4.2. Vibration

For vibration (Figs. 13 and 14), the magnitude of the peaks varies greatly depending on how the pipe is fixed relative to the location where the measurements are being taken. The Nylon5 measurement was subject to an unknown malfunction but was included for completeness purposes since peaks are still visible.

4.2.1. Comparison of location/material

To fully compare the range of thresholdable values, the distance from the highest and lowest peaks to the highest measured noise level was calculated for each FEAT device:

- HPHF – High peak/High Flow – The highest peak in the high flow situations

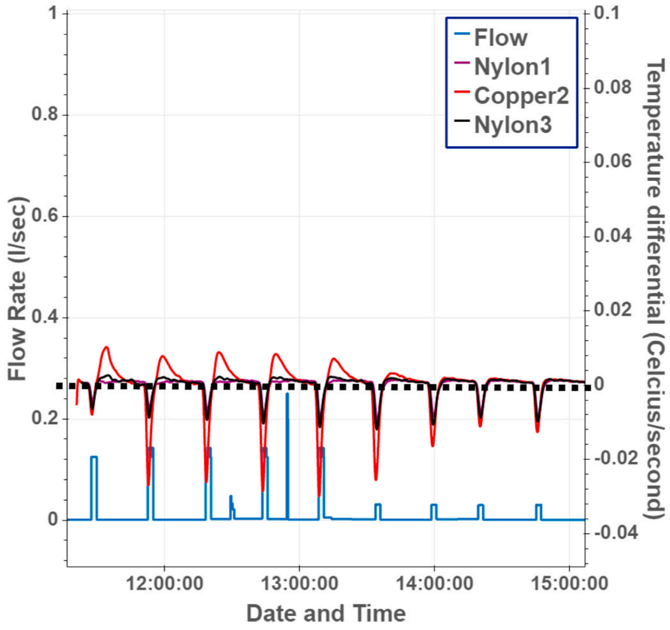

Fig. 11. Cold water differentials with threshold applied (dashed line).

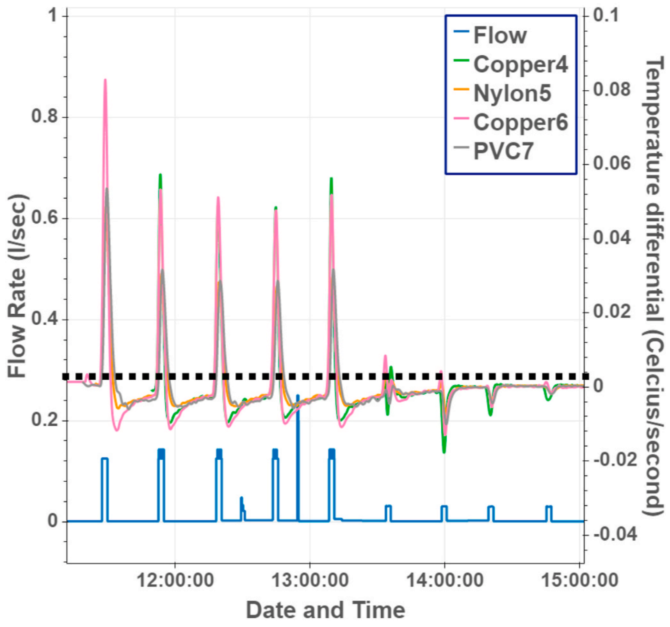

Fig. 12. Hot water differentials with threshold applied (dashed line).

Table 4
Thermal conductivity of tubing materials, adapted from [31].

Piping	Material	W/mK
Steel	Carbon Steel	54
Copper	Copper	401
PEX	Cross-linked High-density Polyethylene	0.51
CPVC	Chlorinated Polyvinyl Chloride	0.14
PE	Polyethylene	0.38
PVC	Polyvinyl Chloride	0.19

- LPHF – Low peak/High Flow – The lowest peak in the high flow situations
- HPLF – High peak/Low Flow – The highest peak in the low flow situations

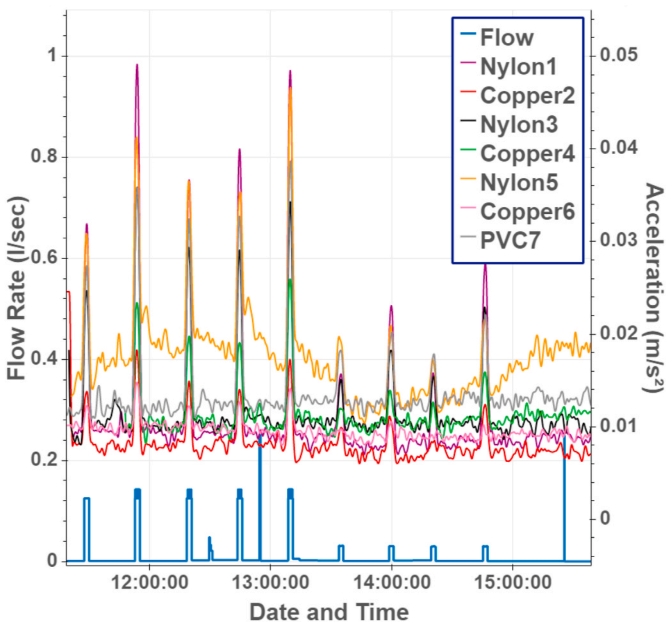

Fig. 13. Acceleration readings for all of the FEAT Devices, including Nylon5 which had an unknown malfunction.

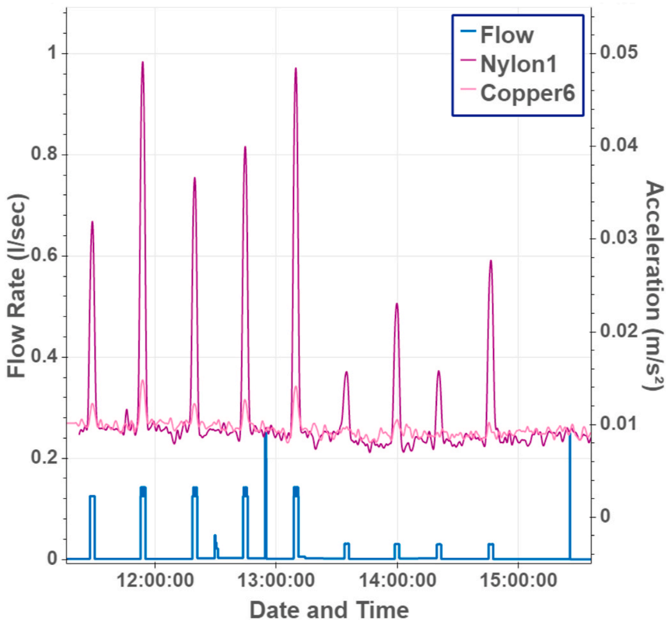

Fig. 14. Strongest detectable result (Nylon 1) vs weakest (Copper 6).

- LPLF – Low peak/Low Flow – The lowest peak in the low flow situations

The results of the calculation are shown in (Fig. 15). In the high flow scenario, all the sensors were able to detect a vibration level over which a threshold could be placed. In the low flow situation, all the scenarios that had the highest peaks were over the threshold, but the lowest peaks were only valid for thresholding for Nylon1, Nylon3 and PVC7. The notable element of these three sensor placements (Table 2) demonstrates that a location where the pipe is less rigidly secured is the most important factor for creating a strong vibrational response. This is confirmed by Copper6 and Copper2 which are close to the point where the pipes are cemented into the wall and Copper4 which is attached to another pipe. This result goes beyond [20] that found the strongest

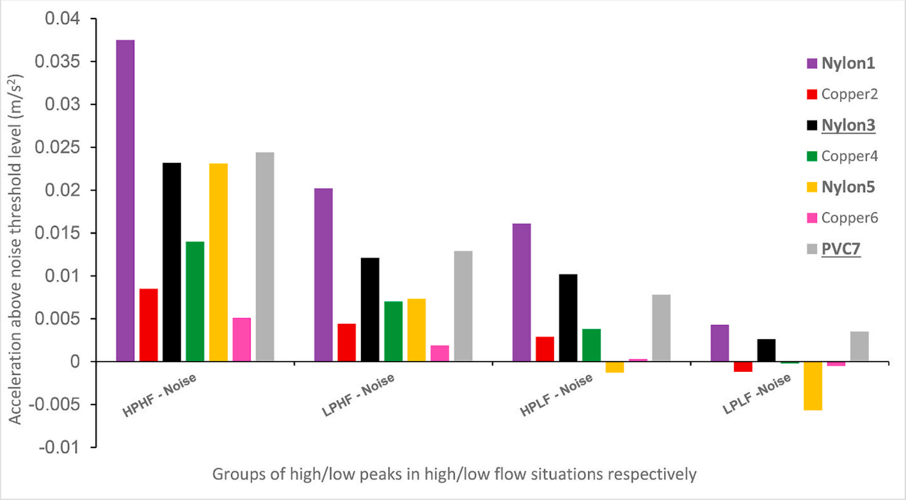

Fig. 15. Grouped chart showing the detectability performance of each topology/material in each scenario, the names in **Bold** for Nylon1, Nylon3, Nylon5 and PVC 7 showing the loosely hanging pipes and the names underlined for those on a bend, Nylon3 and PVC7.

vibration on a pipe bend.

(Fig. 15) shows that in terms of pipe topology, the effect of a pipe with a bend versus a straight pipe was found to be relatively insignificant compared to other factors. Since a straight pipe can outperform and underperform a pipe bend there must be other factors that affect it more. Pipe material cannot be conclusively ruled out, since the copper performed poorly on the vibration results, but it should be noted that another rigid material, PVC, had a stronger result than Nylon3 which is flexible.

Conclusively (Fig. 15) shows that the loosely fixed pipes, Nylon1, Nylon3 and PVC7 were able to vibrate freely and produced a meaningful amount of vibration above the noise threshold level whereas Copper2, Copper4 and Copper 6 that were fixed had significantly less vibration. For future flow detection for disaggregation purposes, it is therefore recommended to place a sensor on the point where the pipe is most easily manipulated. This contrasts with flow measurement, where a fixed pipe is preferable for consistent readings, though flow measurement could be possible for pipes that are not securely fixed, by having a calibration phase, as proposed in [17].

4.2.2. *Using peak values*

An extra feature for determining when flow is active is based on using the peak values from the vibration dataset. When the smoothing is removed, it is possible to see peak values occurring both when there is flow (in green) and when there is no flow (in red), shown in (Figs. 16 and 17). The red peaks can be caused by erroneous values, noise, or external disturbances, which is why a multimodal approach using temperature and vibration will help to remove false positives.

Using a higher sampling rate may boost detection possibilities, since the peaks would occur more often during times of flow [29]. explains how a 250Hz “burst mode” was taken during expected flow, which was then condensed into a 1Hz sample. The amount of battery usage would need to be considered when taking such rapid readings, but at 250Hz, averaging, filtering and smoothing values is more likely to be able to reduce the effect of any noise compared to 1–2Hz readings. This is because a larger sample set is less likely to be affected by random variations and patterns/trends become more apparent due to reduced interpolation.

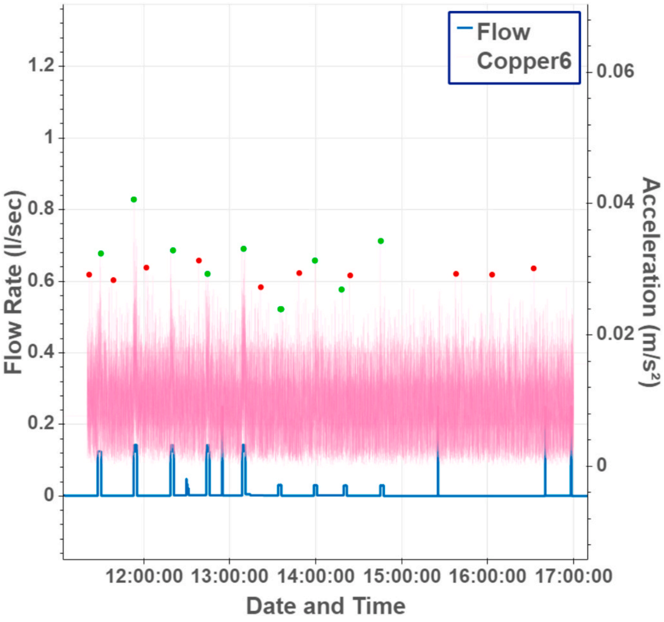

Fig. 16. Peak values on weakest result.

4.3. *Comparisons with previous work*

The most comparable study known to the authors at the time of writing is the [26] paper for the event detection on a water heater using both vibration and temperature differential. The flow rate events used in [26] have a minimum threshold of 0.09 l/s, which is much easier to detect than the 0.03 l/s events used in the FEAT device study. Despite this difference, the FEAT device study was able to generate a result with a clear threshold in both temperature differential for all of the cases in the high flow scenario.

The FEAT study goes beyond the [26] study by considering topology, pipe material, pipe fixing and using both hot and cold water scenarios.

4.4. *Limitations*

The main limitations of the FEAT device study are as follows:

- Only one appliance – different appliances will create additional issues, for instance a washing machine will be a source of vibration whilst operating at high speeds. Future studies will look at applying the FEAT to multiple devices simultaneously to show that the multimodal method can overcome external influences.

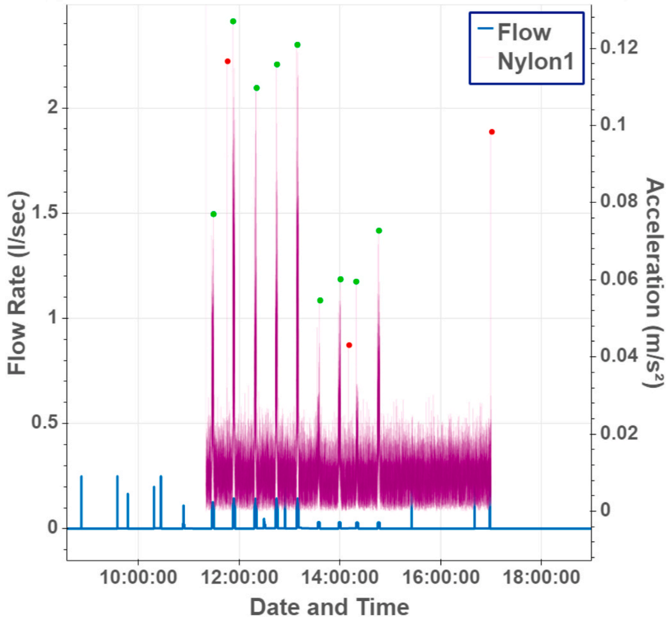

Fig. 17. Peak values on strongest result.

- Does not cover micro events – Events of a short duration will be harder to account for the water usage, particularly events of less than 1L which may not register on the external flow logger. Future studies will look at events of all durations, which will demonstrate the potential of the FEAT device being able to account for extraneous usage, e.g. a dripping tap or leaky toilet.
- No combined events in test experiment – A real-world scenario can have multiple appliances in use at once, potentially interfering with each other. A probabilistic model based on typical appliance consumption will be required to account for these cases, which will be developed in further work.
- Laboratory conditions – In these controlled conditions where everything was monitored it is easier to react to any issues. The field testing will be more susceptible to external factors which will need to be accounted for as they arise, the future work will include multiple households over longer test periods to account for all scenarios.
- Easily accessible pipes – The experiment was setup in a scenario with pipes that are in a cupboard and easily accessible. Future experiments will specifically target households where pipes are accessible, ideally loosely hanging pipes that increase the vibration effect. In the case of inaccessible pipes, it may be necessary to attach the FEAT device to, for example, a toilet bowl or shower head for collecting readings. Further experimentation would be required to deal with the additional external factors in these cases. Through a combination of multimodal sensors and probabilistic modelling, theoretically it would be possible to assess the impact of attaching sensors on showerheads or toilet bowl.

4.5. Future work

Future studies will look at expanding into multiple households and attaching to multiple devices in a real-world domestic usage scenario. Ideally, power usage requirements should be reduced to increase the current battery lifespan of 5 days. Reducing the transmission intervals should help with optimising this requirement, filtering useful data is another possibility for reducing transmission packet sizes. The sampling frequency will also be increased and modified to find the optimum balance between accuracy of readings and battery life.

5. Conclusion

The FEAT device provides a solution to the problem of necessitated ground truth paradigms for residential water flow disaggregation. The FEAT device was able to demonstrate a clear detectable flow in all the high flow 0.13 l/s experiments with a possibility to gain results in some of the most extreme low flow cases of 0.03 l/s.

In terms of vibration, this study provides guidance for achieving detectable flows in these extreme cases of 0.03 l/s, by locating the sensors in positions where a pipe has the most freedom of movement. This will likely be further enhanced using higher frequency sampling (up to 250Hz). The main issue with this type of sensor is false positive readings, due to noise and extraneous influences; the proposed solution is combining with temperature differentials which are less susceptible to external factors and noise.

For the temperature readings, this study was able to show a clear threshold for flow detection in all of the cold water readings and in the high flow readings for the hot water. As expected, the copper pipes showed a stronger response relative to the nylon and PVC, but since a strong response relative to noise was shown for all the material types, sensor placement priority should be attributed to where the strongest vibration result will be possible. The main difficulty with this sensor is in the case that the boiler is not triggered for hot flows since cold water will be flowing through which will not trigger the hot water threshold. In these cases, a more complex model will be needed to be applied for unaccounted water usage.

The vibration and temperature combined solution using the FEAT device is a suitable low-cost solution that accounts for water usage disaggregation for a flow trace. The ability to create large datasets using these devices will allow for increased accuracy of appliance identification relative to conventional methods. This emerging field of disaggregation datasets from IoT devices shows great promise in the future towards helping understand domestic customer usage and the low-cost, non-intrusive, highly scalable FEAT device potentially provides a cost-effective and simple solution towards future water conservation targets.

Credit author statement

Paul Wills: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing – Review and Editing, Visualization. **Fayyaz Memon:** Conceptualization, Writing – Review and Editing, Supervision, Project administration, Funding acquisition. **Yulei Wu:** Conceptualization, Writing – Review and Editing, Supervision. **Paul Merchant:** Conceptualization, Resources, Writing – Review and Editing, Supervision. **Malcolm Roberts:** Conceptualization, Resources, Supervision.

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.

Data availability

The authors do not have permission to share data.

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