Transition from Observation To Knowledge To Intelligence (TOKI)

Editors

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Pipeline Surveillance and Leakage Detection System with IoT and UAV

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Abstract. The effective and efficient monitoring and surveillance of oil and gas pipeline network; the most common form of hydrocarbon products is a key issue today. When these tasks are given out to humans in some cases, they tend to underperform these roles and are sometimes prone to dangers. Yet the problems that arise from inefficient and ineffective monitoring can be very harmful to society and the environment. For this reason, researchers have come up with various ways of trying to perfect these tasks and these solutions range from sensing the functional and nature of the pipelines through the use external sensing techniques, vision and interior computation methods. Our proposed solution involves the unification of these methods with the use of IoT, artificial intelligence and UAV; with this, we tend to harness results from these areas to improve the overall efficiency and achieve a high degree of automation. After a systematic evaluation of results, we discovered this process requires a varied level of expertise but comes with the potential of creating a relatively feasible solution to the problem.

Keywords—Pipelines, oil and gas, IoT, UAV, Sensors, fuzzy logic, monitoring, surveillance, automation

1. Introduction

Pipelines are a series of connected tubes utilised in the carriage and transportation of water, oil or gas over a long distance. In the Nigerian oil and gas industry, most of the petroleum products are sent to retailers using pipelines, while other methods include using the sea (barges), tankers (road) and railroad tankers. Pipelines have been used to transport petroleum products since in Nigeria since 1978. The Department of Petroleum Resources (DPR) stated that the pipeline network is composed of 5,000 KM of product pipelines and 16,000 KM of the combination of both crude oil and product pipelines (Eze, 2017); These figures are similar to what other researchers have found (Anifowose, Lawler, van der Horst, & Chapman, 2012),(Monitor, 2013). Some of these pipelines are made up of legs of different lengths, with some ranging up-to thousands of kilometers. These pipelines can have diameters of about one meter.

During the transportation of crude oil and petroleum products equipment failure such as breakage or leaks can occur for many reasons which include but are not limited to over-age of structures and material failure, natural ground movement, accidental hot-tap and third-party (intentional, incidental and accidental) interference(CONCAWE, 2013). During the event of these pipe failures, a large amount of gas can be lost and more vital the release of these hydrocarbon leaks can damage the surrounding environment through pollution and contamination, it can also affect the ecological health and safety of humans. Many countries have recorded a variety of these catastrophic events. For instance, in Nigeria during the 2000s vandalised pipelines have exploded or leaked and this has led to thousands of fatalities. Record depicts that about 18,667 incidences of vandalism occurred between 2002 and 2011 in Nigeria; in Belgium a natural gas pipeline exploded in 2004 killing 24 people; in Canada gas transmission pipelines exploded and burned in January 2014; In Michigan, USA, in 2010 corrosion and fatigue cracks caused a pipeline to leak and spillover 3000 m^3 of crude oil into the Kalamazoo River after the event hundreds of residents living in the affected areas suffered health effects relating to the toxic exposure from the oil and the clean-up costs 800 million USD. Also, minor incidents happen more frequent than catastrophic events and they pose a danger to the environment and causes economic loss. The Nigerian National Petroleum Corporation recorded 194 cases of pipeline vandalism in 2017. Ageing of oil and gas pipelines makes them more prone to corrosion and failure and this would require frequent inspection and prediction mechanisms to be put in place to prevent incidents that could harm the environment, people and economies. Incidents of thefts have increased in recent years in both oil and gas pipeline networks and these events have become one of the major causes of oil spillage. These spillages have adverse effects on vegetation(QianXin & Mendelssohn Center for Coastal, Energy and Environmental Resources, Louisiana State University, Baton Rouge, LA 70803 (USA)), 1996)(Mishra DR, Cho HJ, Ghosh S, Fox Z, Downs C, Merani PBT, Kirui P, n.d.), wildlife (Heintz RA, Rice SD, Wertheimer AC, Bradshaw RF, Thrower FP, Joyce JE, 2000), and fresh and ocean water (Bennett PC, Siegel DE, Baedecker MJ, 1993). Finding efficient and effective ways of monitoring and maintaining these pipelines are of crucial importance for the protection of the environment.

In the monitoring and maintenance of these pipeline networks, there is a need to accurately monitor the structural conditions of the pipeline so that pipeline failures can be prevented, proper maintenance and repair strategies can be carried out. During the inspection of these pipelines, the members of the surveillance team may experience fatal explosions and life-threatening situations (during vandalism) and for that reason a solution with a high level of automation is important. In this paper, the overall application of IoT and UAV is designed to detect and the monitor real-time situation of the structural and functional status of the pipeline and to perform proper surveillance to inform the type of maintenance that should be carried out. The use of UAVs to perform the surveillance will save lives by preventing the members of the surveillance team to be present in the event of an explosion or oil theft. Besides, the data from the sensors can also be used to carry out a certain degree of predictive maintenance. In section 1 the background and the significance of the study is demonstrated. In section 2 existing methods of the utilization of IoT and UAVs to monitor pipelines are reviewed. In section 3 our unique methodology and materials of implementation are demonstrated. In section 4 we discuss the advantages and limitations of our method. Lastly, the conclusion and prospection are shown in section 5.

2. Literature Review

Some remarkable attempts have been made in trying to offer leak detection mechanisms in (Adedeji, Hamam, Abe, & Abu-Mahfouz, 2017) they pointed out two types of leakages (1) burst type leakage - is easily detected and thus makes repair time faster, when compared to repairs on damages caused by (2) background leakages - not easily detected. They developed an algorithm that uses pressure sensors and flows meters to estimate and detect the background leakage flow. Although they were able to demonstrate the ability of the algorithm to detect these hard to find leakages, the work was not able to locate the exact point of leakage.

In (Lukman, Adedokun, Nwishieyi, & Adegboye, 2018) a piezoelectric sensor, a GSM/GPS Module was used to create an anti-theft oil pipeline vandalism detection system. Here the piezoelectric sensor which was connected to an Arduino board was used to sense vibrations on the pipelines and when the vibration surpasses a threshold an alert SMS is triggered and sent to the surveillance/monitoring team. However, this method of approach will not be able to capture certain types of leakage and vandalism for pipes that possess a diameter of one meter and are made up of alloy steels; even when these pipes are being vandalised the level of vibration can be less than the specified threshold. Also, not all vibrations may lead to vandalism or leakages, so a more efficient and effective system is needed.

Instead of using vibration signals, in (Ai, Zhao, Ma, & Dong, 2006) a leak detection mechanism was developed using acoustic signals; with a consolidation of Linear Prediction Cestrum Coefficient (LPCC) and a probabilistic graphical model – Hidden Markov Model (HMM) damaged acoustic signals were examined and analysed to detect damages or leaks on the pipelines. The acoustic signal recognition accuracy was up to 97%. This study shows how the use of machine learning algorithms can be useful in detecting leaks. However, the effect of background noise can be a limitation as it tends to mask the actual sound leak. Accelerometers (vibroacoustic devices) have also been utilised to develop these leak detection systems. In (Ai et al., 2006) wireless accelerometers were used to detect leakages on the external area of valves connecting pipeline networks.

In (Eluwande & Ayo, 2016), a study was carried out to use Unmanned Aerial Vehicle (UAV) machinery for real-time monitoring and surveillance of a pipeline network in a hazardous environment. The UAV was used to inspect and report the status of the oil pipeline through live video coverage. However, it was always of a necessity for a human to be there to assist in the monitoring and there was inadequate information about the structural and functional status of the pipeline. This implies that the information about the status of the pipeline was dependent on only what the UAV could see.

In (Obodoeze, Asogwa, & Ozioko, 2014), an oil pipeline vandalism detection and surveillance system were developed using an intruder detection system. Here a video camera was integrated close to the pipeline for surveillance and to capture the identity of the culprit. This system seems to be quite efficient but there was no provision for a sabotage countermeasure.

Other methods of leak detection system which includes the interior-computational models utilise internal fluid measurement instruments to monitor parameters associated with fluid flow in pipelines for instance in (Rashid, Qaisar, Saeed, & Felemban, 2014), an automated, noninvasive and rapid method of oil pipeline leak detection was proposed with the use of a distributed signal processing technique which employs discrete wavelet transform to extract critical inflection points of negative pressure wave (NPW). Here a distributed decision making is employed to reduce the workload of the base station. They claim that the use of this method has led to the reduction of false alarm rate effectively and has improved detection and location precision. The devices used for data collection are Wireless Sensor Networks; this was used to design a pressure-based leakage detection system. However, this work fails to cover a predictive maintenance feature for distribution pipelines. Also, in (Rougier, 2005), a means of detecting leakages in pipeline networks using the mass-imbalance technique was proposed; in the work, the activities of calibration and prediction were combined to infer the presence and attributes of leakages.

Digital signal processing methods have also been employed in the detection of leakages in pipelines. In deploying this method, the extracted information such as amplitude, wavelet transform coefficients and other frequency response is used to determine leakage events. The fundamental steps include: (1) Internal sensors measure in pipe pressure or flow; (2) Data acquisition stage requires pre- processing and removal of background noise (3) Feature extraction stage that involves some spectral and signal transform techniques to extract some relevant features to monitor the hydrocarbon fluid transmission in the pipeline; (4) The pattern of the extracted feature signals is compared with labeled signal features for decision making;(5) Leakage detection is accomplished using an already established threshold. In (Liu, Li, Fang, & Xu, 2019) a small leak feature extraction and recognition scheme were proposed for natural gas pipelines using some digital signal processing techniques. Based on these features the principal product function components that possess high information content about leaks were used for further processing.

This paper focuses on the development of a hybrid method of detection. Unification of the exterior sensing methods (accelerometer), visual method (Unmanned Aerial Vehicle with camera) and the interior computational method (pressure based) are employed to create leak detection and surveillance systems for oil and gas pipelines.

3. Materials and Methods

The materials used for the development of this system possess both the software and hardware components. The hardware sub-system includes the:

- Hardware components used to monitor the structural and functional status of the pipelines.
- UAV hardware component used to give a visual status of the pipeline network.

The software sub-systems include the software modules used to:

- Activate and visualise the sensor readings, to achieve sensor communication, data transfers from the deployed test site to online FTP Server,
- Cloud-based data analytics and
- Autonomous software module for the UAV flight.

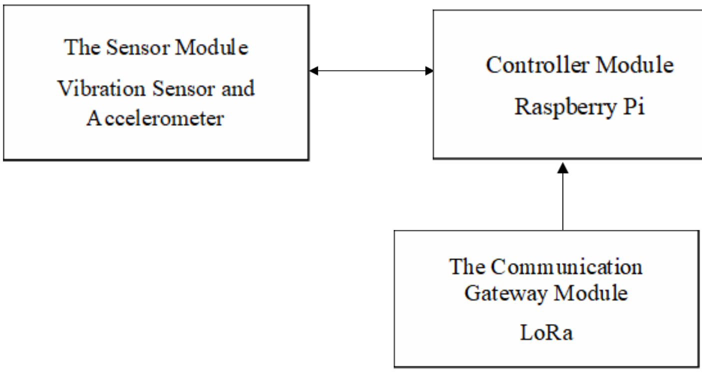

Figure 1: Block Diagram of Pipeline Structural and Functional Monitor

The hardware subsystem for the sensor readings to monitor the structural and functional status of the pipelines and the actualization on the pipeline test bed can be categorised into three (3) modules

- The Controller Module
- The Sensors Module
- The Communication Gateway Module

The hardware subsystem component of the UAV used to give a visual status of the pipeline.

In choosing hardware for the UAV we considered the following:

- Compatibility with other components
- Lightweight
- Cost
- Ease of integration in the system and

- Flexibility of firmware

3.1. Communication and Control

Considering the automatic pipeline network surveillance methodology employed in this project the following implementations were carried out in the section of the project that involved communication.

There are two ways of establishing communication between the ground station and the drone using Wi-Fi technology (as it's the most efficient method for long-range flight) while in flight namely; use of 4G mobile dongle and the use of LoRa module. But in this project, we employed the used of both ways for experimentation and analysis purposes. Communication using the 4G dongle and the LoRa module between the drone and ground station can only be made with an intermediary component like Raspberry Pi having a 4G modem connected as in the former Although, there are some limitations concerning this type of Wi-Fi connection, in order to get telemetry information, the dongle installed on Raspberry Pi must have a good Wi-Fi antenna power for a higher maximum range and in the second method, a LoRa module is connected to the raspberry pi which provides it with network access for data exchange with the flight controller (ardupilot).

To establish communication between the flight controller and fuzzy logic algorithm running on Raspberry Pi, both ends need to use the same messaging protocol (MAVLink) to make communication possible. In this project, the MAXProxy protocol was used which serve as a MAVLINK message gateway whose main goal is the exchange of MAVLink data between the flight controller and the fuzzy logic algorithm running on the Raspberry Pi. This is achieved by ensuring that the algorithm always runs on the Raspberry Pi.

3.2. Autonomous Navigation

To have an autonomous system, we ensured that the control system understands waypoint information from Google earth in the form of coordinates (mainly longitudes and latitudes) with the help of GPS and calculates the distance between the take-off base station to the target location. We developed a web console with some functionalities like arm drone, snap image, land, take off, autopilot that is issued to the drone as shown in the figure below. Sensor readings in the form of coordinates from the pipeline's setup are received on the web console such that it automatically triggers the drone to fly to the target location.

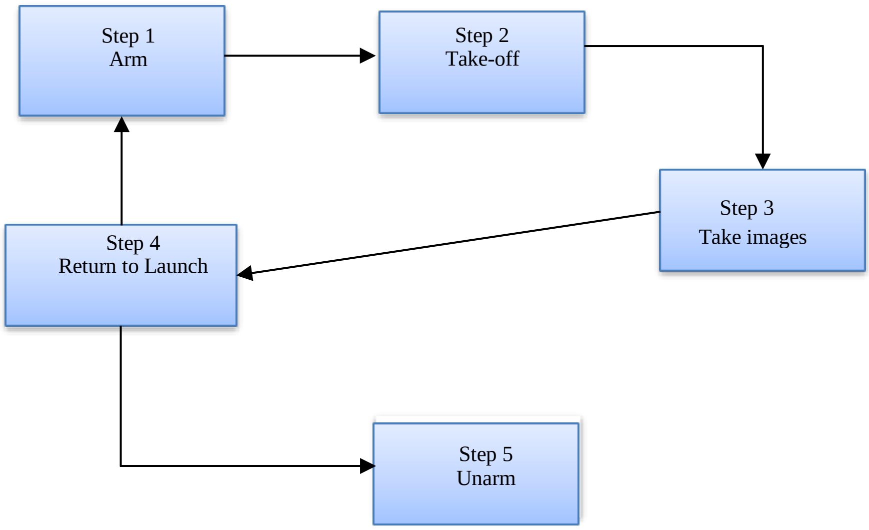

Figure 2: Block Diagram of the autonomous steps of the drone with web-console control.

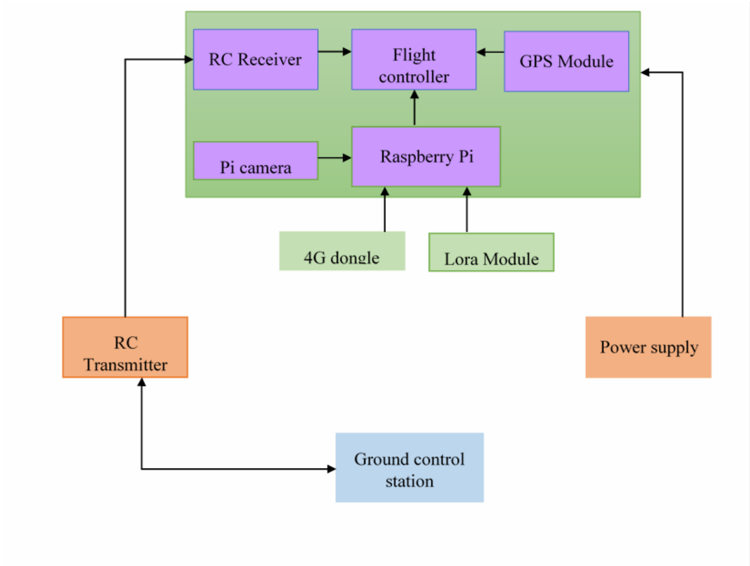

Figure 3: Block Diagram of Autonomous Quadcopter

To ensure robust surveillance and leak detection for the system for the pipeline network the unification of the exterior sensing methods (accelerometer), visual method (Unmanned Aerial Vehicle with camera) and the interior computational method (pressure-based detection) were employed.

When using a pressure sensor alone, discovering a leakage takes a longer time when compared with the method adopted in this project, furthermore if a small leak occurs the pressure drop may be insignificant and thus not detected by the pressure sensor. This drawback can be exploited by a vandal, by tapping a small diameter the vandal may create an aperture just small enough to tap oil without triggering the pressure sensor, thus a more robust method is needed, one that involves multiple sensors.

Using an accelerometer some minute vibrations was detected. Vibrations caused by drilling often exhibit a standard pattern which can easily be classified by a neural network, similarly a vibration caused by hammering can exhibit a particular pattern which can be classified by a neural network, earth tremors, landslides, explosions all exhibit a particular pattern which can be classified by a neural network, with this knowledge a system we can have the ability to predict a likely pipeline attack, and possible actions to mitigate the chance of oil loss can be taken.

The combination of pressure and vibration sensor makes a foolproof method to detect any form of pipeline damage and offers a predictive protection layer. Cracks due to stress can occur along a pipeline these can be picked up by the accelerometer and classified by a neural network.

The exact location of vandalism can be detected by measuring the intensity of the vibration between two sensors, the closer a vibration is to a sensor the more intense the vibration is detected on that sensor, gradually the intensity of the vibration decreases further away from the sensor, using this 2D information the location of the vandalism and perhaps leakage can be estimated.

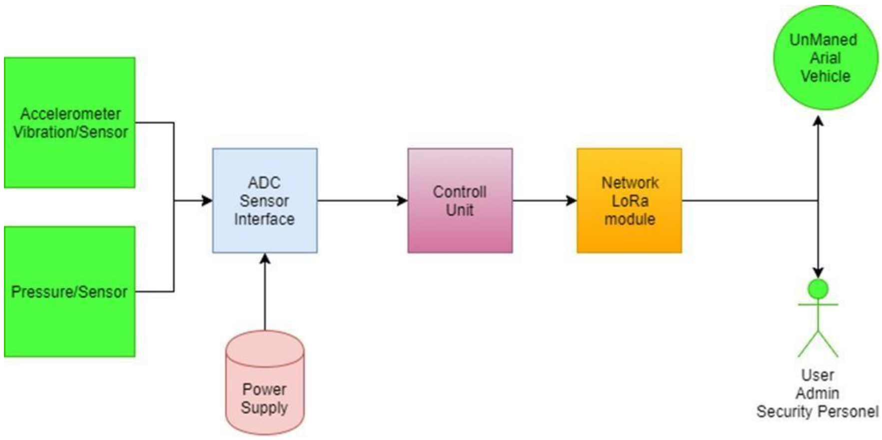

Figure 4: Multi-sensor approach for pipeline monitoring

Figure 4 shows a block diagram of the multi-sensor approach used in the project. This shows a summary of both the hardware and software components used to design the system; it typically consists of a Raspberry Pi as the onboard computer, a 5V power supply, and a LoRa WAN module for long-range communication. The system can relay information to a drone and the security personnel. In Figure 5, the pressure and accelerometer readings are shown on a web interface we designed.

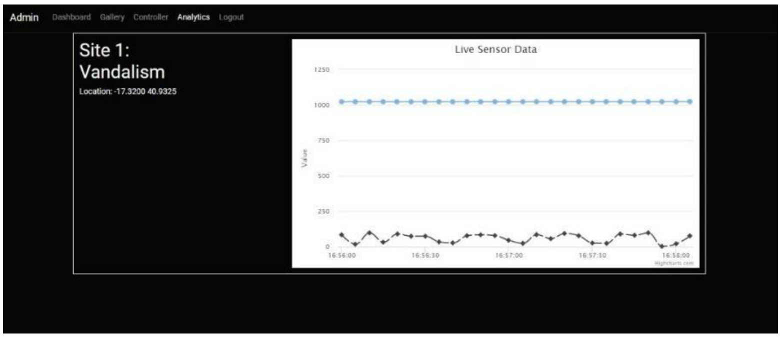

Figure 5: Screenshot of Vibration (black) and pressure (blue) readings

4. Evaluation and Discussions

This paper proposes a system to monitor and detect pressure drop and the vibration is an automated and efficient way. The parameters employed in this system cover the three techniques considered in this project. Fuzzy logic was used to monitor the vibration and pressure parameters coming from the pressure and vibration sensors; the patterns recognised by this algorithm enable the surveillance system to take necessary actions. For this project, we considered three different levels of threat. With the fuzzification process, these levels of threats were encoded. As fuzzy logic approaches computing methods that regards the degree of truth rather than Boolean or discrete values; membership functions were defined to give a suitable method of detection. The membership functions allow us to visualise a fuzzy set. Conventional standards suggest that x-axis represents the universe of discourse and the y-axis represents the degree of membership in the [0, 1] interval.

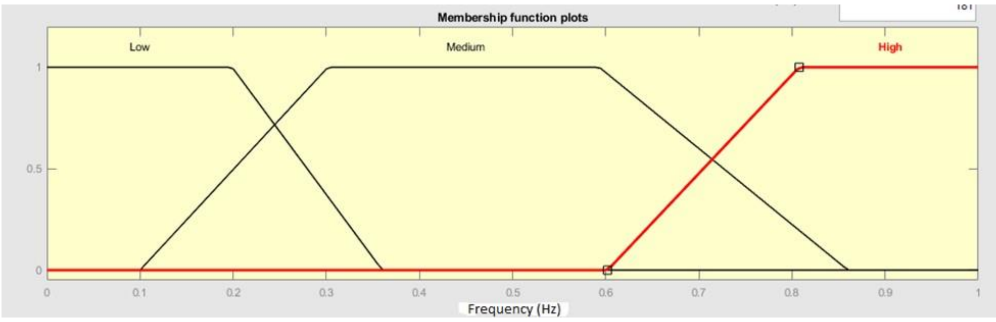

Figure 6: Membership function for accelerometer

To further clarify the fuzzification process Table 1 shows the fuzzy rules used to calculate the degree of truth of the possible vandalism and leakage events.

Table 1: Fuzzy rules used to calculate the degree of truth of the possible normal and abnormal events.

		Pressure		
Vibration	AND	High	Medium	Low
	High	Abnormal	Abnormal	Abnormal
	Medium	Normal	Abnormal	Abnormal
	Low	Normal	Normal	Abnormal

The normal or abnormal states detected by the system are the trigger needed for the drone to respond.

4.1. Image Analytics

Once an abnormal event is detected the drone will be triggered; the drone will be sent to the location to take pictures around the location of the suspected abnormal event to provide more insight to its classification by sending the images back to the base station, these images are analysed to provide an appropriate response. It is sometimes necessary to know the state of the pipeline infrastructure before deploying the response team, there may be a fire, or the vandals may still be present on-site and armed.

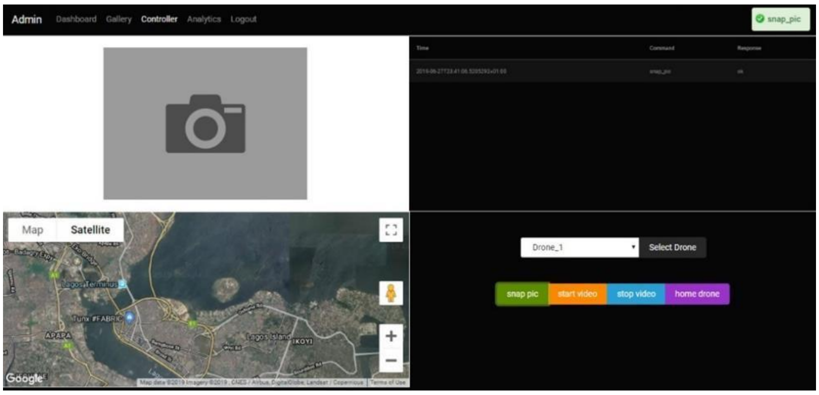

Figure 7: Screenshot of web-console with images and of the drone capture and the location of the drone.

5. Summary and Conclusions

The wide network of oil and gas transmission pipelines in Nigeria makes up a huge system of safe transport. With time the monitoring and surveillance of these pipelines will substitute the conventional methods. This can lead to more lives being saved and increase the efficiency and effectiveness of the maintenance of the pipelines. In this study we created a platform for monitoring the structural and functional status of the pipeline in order to use the results obtained from the monitoring system to trigger the drone when the case of leakage or vandalism is encountered. In this work we used the fuzzy logic algorithm to consolidate the readings obtained from two sensors (pressure and vibration). For further work we suggest we plan to use a neural network to understand form a knowledge base of various vibration and pressure patterns to detect leakages and predict vandalism. We were able create a web console that will facilitate the monitoring of the UAV. In order to improve this work, we will need to consider more parameters, and include digital signal processing to reduce false alarms and gain higher precision.

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