Leveraging on Low-Cost Devices for Wireless Data Acquisition in Remote Pipeline Networks

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ABSTRACT: Pipeline infrastructures are the most used means of transporting oil and gas from extraction point to production and sales point. These pipelines are exposed to various attacks either by natural occurrences, indiscriminate human activities around pipelines or direct criminal sabotage, and therefore require constant monitoring. The use of low-cost wireless devices for pipeline data acquisition as it applies to remote and difficult terrain is presented. Different methods and models have been suggested in literature with several existing systems such as SCADA, DCS, and satellite spectral imaging currently in use for pipeline operations. Among the challenges here is the need for lower operational costs, even at reduced response time demand. The Wireless Data Acquisition System (WDAS) presented simulates a pipeline system in a testbed in which a petroleum product is caused to flow and its parameters read, processed as data and wirelessly transmitted, through a wireless sensor network, to a remote device for monitoring. Results indicate a very short response time of about 3.0sec in the simulation at a percentage accuracy of 0.07% over 1km. It also shows that low-cost wireless sensor networking can provide a cost-effective means for pipeline infrastructure management and should be explored.

KEYWORDS: Parameter, Sensor, Network, Processing, Testbed, Simulation

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NOMENCLATURE

Vs	Sensed pressure signal (V)
Ve	Wheatstone Bridge excitation voltage (V)
GF	Gauge factor
ε	Strain
Rg	Undeformed gauge resistance (Ω)
Δ***R***	Change in strain gauge resistance (Ω)
Q	Flow rate (m3/s)
V	Fluid velocity (m/s)
A	Pipe cross-sectional area (m2)
$\bar{r}$	Pipe radius of in meters (m)
ω	Angular velocity (m/s)
ς	Number of blades
A	Angle between flow direction and turbine blades (0)
R	Resultant radius of outer and inner blades (m)
B	Distance between blades (m)
Ro	Outer radius of blade (m)

I. INTRODUCTION

In the petroleum industry, pipelines are the major means of transporting crude and its associated products from one place to another (Allison & Mandler, 2018). These pipelines can pass through remote areas such as underwater, over hills and mountains, mangrove forests and swamp areas (Stoica, *et al.*, 2016). The maintenance of the economic progress of oil-producing countries is largely dependent on efficient monitoring through data acquisition from these oil and gas infrastructures. Such data acquisition, especially in remote locations can help to prevent failure, detect leaks as well as initiate maintenance and repair activities on time (Ameh *et al.*, 2017).

Several pipeline parameters are monitored and acquired through different technologies designed to report the needed pipeline system's status per time (Khan *et al.*, 2021) (Singh *et al.*, 2021). Typical of such parameters are pressure, flow rate, temperature, viscosity, and so on. The existing methods, which include manual inspection using trained dogs, Supervisory Control and Data Acquisition (SCADA), Distributed Control System (DCS), and also recently advanced satellite-based hyperspectral imaging methods, look promising but with certain drawbacks such as cost-effectiveness and slow response time as pointed out in (Adegboye *et al.*, 2019;

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Upadhyay & Sampalli, 2020; Febaide & Uzedhe, 2021; Ejofodomi & Ofualagba, 2017).

These drawbacks are a bane to increasing demand for real-time responsiveness within a lean budget. This paper seeks to provide a fast and cost-effective solution for pipeline infrastructure data gathering with low-cost devices.

II. REVIEW OF RELATED WORK

Several authors have researched and presented findings on the application of wireless devices in pipeline scenarios. Gong *et al* (2016) developed a mobile sensor-based wireless sensor network used for inside water pipeline applications. The sensors transmit the collected data to a fixed access point. Location accuracy is achieved using Integer Nonlinear Programming. This could only be tested on water pipelines as its certainty of working for petroleum pipelines was not ascertained. Abbas *et al* (2018) worked on Wireless Sensor Networks (WSN) with a focus on key factors involved in pipeline monitoring techniques but did not consider the product parameters in relation to the pipeline operation. Ayadi, *et al*. (2022) analyzed pipeline monitoring technique models on both wired and wireless sensors in a bid to validate that WSNs are more effective in pipeline monitoring and data acquisition. Their work only emphasized water pipelines and could not validate for other pipeline networks like petroleum pipeline networks.

Rea-time WSN-based remote monitoring system for an underground pipeline by Abdulwahab (2022) is capable of monitoring real-time data of the pipeline cathodic protection (CP) system and transmitting such data remotely through short message service (SMS) and the Internet of Things (IoT) technology to the control room. The system however is incapacitated when there is no Global system for mobile communication (GSM) network; and does not capture the data of the fluid flowing through the pipeline.

Rehman & Nawaz (2017) in their reviewed work provided in-depth insight into the use of wireless sensor networks as a solution tool in detecting different pipeline leakages. They further made helpful recommendations for future advances in the use of WSN for data acquisition and alerting personnel of possible leaks remotely. Similarly, Varghese *et al*. (2018) developed a pipeline control and monitoring system that utilizes a mobile application to isolate valves and monitor pipeline elements. The time interval of data reception is slow and is dependent on GSM mobile network.

III. METHODOLOGY

An experimental pipeline platform on which sensing devices are fixed at intervals was developed to mimic the operation of a real-life pipeline system. The wireless sensing devices, Sensor Node (SN), pick up signals from the pipeline and send the same as data to a remote device for collection, presentation and possible control feedback. The application of parameter sensors, SN and Remote Node (RN) devices, form a Wireless Data Acquisition System (WDAS) that will function to acquire real-time data from the pipeline for monitoring and control.

The experimental pipeline is made up of 30m long PVC pipe interconnections, a 0.5m³ reservoir, 1 Horse Power (HP) oil pumping machine, and valves to simulate leaks as shown in Figure 1. Install into this testbed at intervals are temperature, flow, and pressure sensors for pipeline parameters sensing. Signals from each of these sensors are read by a connected SN, conditioned, processed as data and converted to a format transmittable in an established protocol to remote devices for data accumulation and presentation.

To demonstrate the operation of a pipeline system, the reservoir was filled with used petroleum oil and pumped, with the aid of the pumping machine, around the PVC pipe connections and back into the reservoir. The flowing fluid temperature, pressure and flow rate are then monitored and recorded by the WDAS as the valves are opened and closed to simulate leaks.

A. *Data Acquisition Process*

The data acquisition process is carried out in four different stages as depicted in Figure 2, from the point where signals are picked up from the field to the receiving end where the pipeline data are presented for possible operational decision-making. The parameter sensing stage involves the use of sensors to read the pipeline parameters of pressure, flow rate and temperature respectively.

At the signal conditioning, preprocessing and aggregation stage, the parameters are scaled to the SN device current and voltage requirement, converted from their analogue form to digital representation, and stored temporarily. So, each aggregator holds an array of 12-bit digital representations of pressure P, flowrate F, and temperature T as [P_n, F_n, T_n]. This information is then processed and accumulated in the next stage as shown in Eqns. (1) and (2) and communicated to the final stage for logging and presentation.

$$D_t = \sum_{t=1}^{t=N}\sum_{n}^{N}(P_{nt}, F_{nt}, T_{nt}) \tag{1}$$

$$Dt = \begin{bmatrix} \begin{bmatrix} P_{1,1} & P_{1,2} & .. & P_{n,1} \\ P_{1,2} & P_{2,2} & .. & P_{n,2} \\ .. & .. & .. & .. \\ P_{1,t} & P_{2,t} & .. & P_{n,t} \end{bmatrix} \begin{bmatrix} F_{1,1} & F_{1,2} & .. & F_{n,1} \\ F_{1,2} & F_{2,2} & .. & F_{n,2} \\ .. & .. & .. & .. \\ F_{1,t} & F_{2,t} & .. & F_{n,t} \end{bmatrix} \begin{bmatrix} T_{1,1} & T_{1,2} & .. & T_{n,1} \\ T_{1,2} & T_{2,2} & .. & T_{n,2} \\ .. & .. & .. & .. \\ T_{1,t} & T_{2,t} & .. & T_{n,t} \end{bmatrix} \end{bmatrix} \tag{2}$$

Eqn. (2) represent data accumulation in the device storage and presents the ease of communication of these data for logging with a simple protocol.

B. *Parameter Sensors*

Three basic parameters of importance were considered to include pressure, flow rate, and temperature that primarily captures the characteristic behaviour of a pipeline system. The parametric signals are sensed and picked from the pipeline with the aid of some specific sensors. Several such sensors are

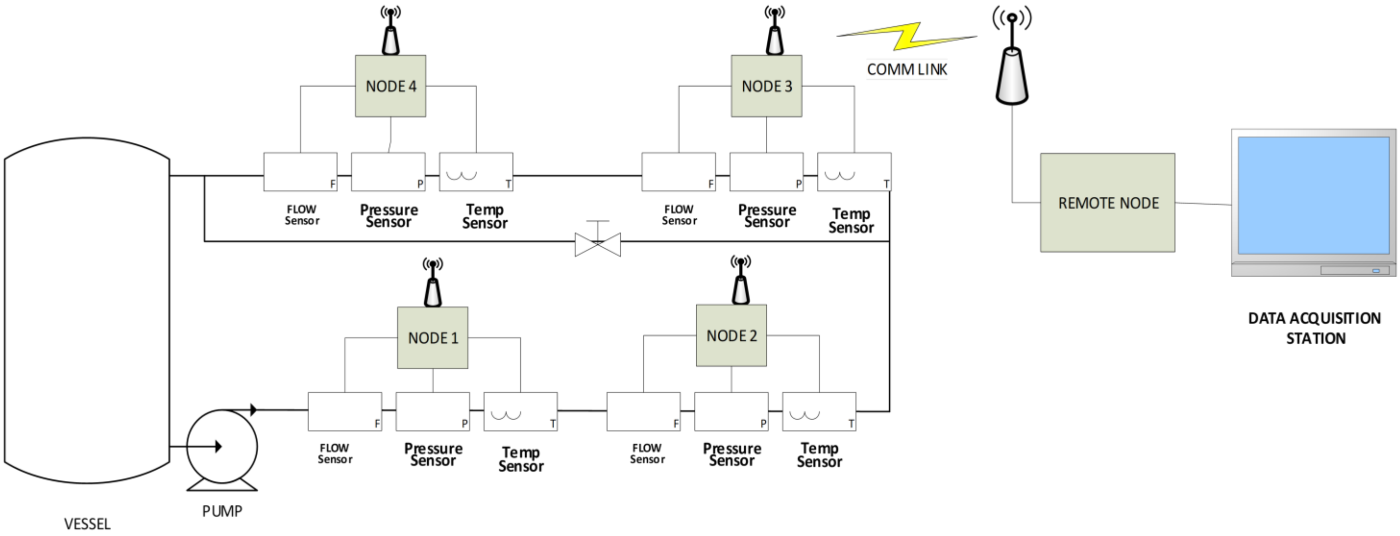

Figure1: System design diagram

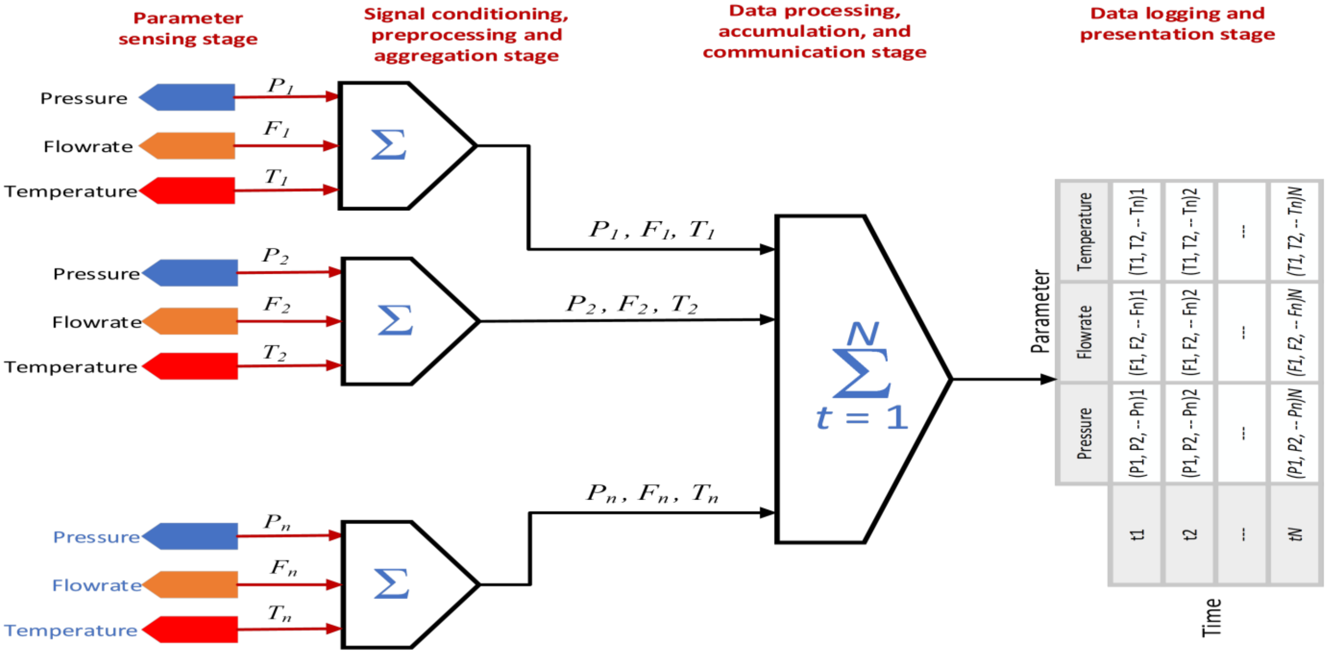

Figure 2: The pipeline data acquisition model

Figure 3: Pressure sensor (Maxim, 2019)

present in the market for the measurement of each of these parameters concerning their operational principles.

1) Pressure sensor (HK1100C)

The piezoelectric device shown in Figure 3 senses the amount of pressure imparted by the flowing oil in the pipeline. The flowing fluid pressure deforms a diaphragm linked to a strain gauge to produce an electrical proportionate voltage variation of the pressure as indicated in Eqns. (3) and (4) such that:

$$V_s = \frac{1}{4}(V_e \times GF \times \varepsilon) \tag{3}$$

$$GF = \frac{1}{\varepsilon} \times \frac{\Delta R}{R_g} \tag{4}$$

HK1100C can withstand a maximum pressure of 1.2MPa and runs on a 5V dc supply to produce an analogue output voltage range of 0.5V to 4.5V.

3) Temperature sensor (DS18B20)

The content and nature of the flowing crude oil results in temperature increase due to viscosity in addition to the external temperature variations along the pipeline. The temperature of the flowing fluid along the pipeline is therefore a critical factor in maintaining operations. The DS18B20 (shown in Figure 5) senses this temperature and produces a digital signal equivalent to the temperature at a resolution of 9-bit to 12-bit. With an accuracy of ±273.65K, the DS18B20 can measure temperatures of 218.15K to 398.15K at an operating voltage range of 3V to 5.5V DC making it suitable for the experimental testbed.

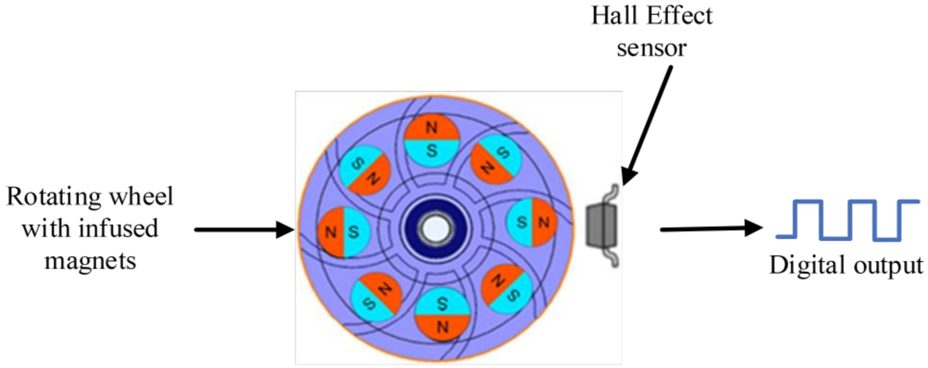

Figure 4a: Hall Effect flow meter operation (Nogaj, 2022)

Figure 4b: Flow sensor (Zn, 2021)

Figure 5: Temperature sensor (Invento, 2021)

2) Flow sensor

The applied flow sensor as illustrated in Figure 5, uses a Hall effect device fixed at a point to pick up magnetic field variation on a rotating wheel on which alternating poles of magnets are mounted. The varying magnetic effect on the sensor generates digital square wave signals from the Hall effect sensor whose frequency is directly proportional to the flow rate of the passing fluid concerning Eqn. 5.

$$Q = AV = \frac{\omega(\bar{\underset{\cdot}{r}})^2 A^2}{\bar{\underset{\cdot}{r}} A \tan\alpha - 0.037\,\mathrm{Re}^{-0.2}\,\varsigma(R_o + R_i) B \sin\alpha} \tag{5}$$

The signal generated by the Hall effect mechanism of the applied sensor is at a maximum of 50,000 pulses per meter cubic and represents a flow rate of 0.112 cubic meters per second (m^3/s).

C. Data Nodes (SN and RN)

The data nodes take on the functions of data preprocessing and aggregation (SN), and data processing, accumulation and communication (RN) as discussed in section A, and are driven by ATmega328P AVR microcontroller as the processing unit in different circuits configurations and functionalities. As shown in Figure 6, each SN is directly connected to field sensors and conditions the sensed signals to their required levels. It preprocesses analogue signals to their digital format, and as well temporarily stores the sensor data for onward transmission to RN. In a setup, the SN and RN operate and communicate through a wireless radio transceiver (nrf24101+) at a maximum frequency of 2.4GHz over a distance of 1.1km at a data rate of 250kbps with a latency of 70µs.

IV. RESULTS AND DISCUSSION

Implementation of the testbed fitted with the sensors as shown in Figures 7a and 7b was done first and the Nodes fabricated into compact casings, as indicated in Figure 7c, were installed. During the runtime, real-time data were obtained

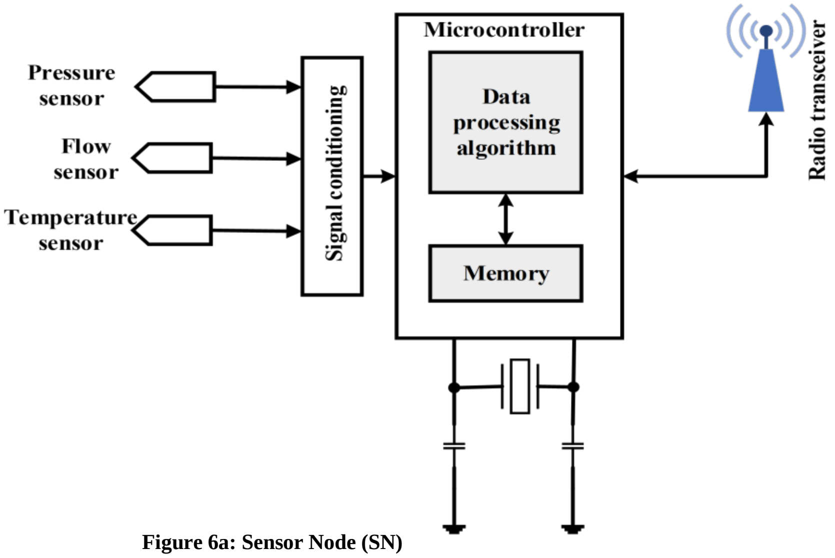

Figure 6a: Sensor Node (SN)

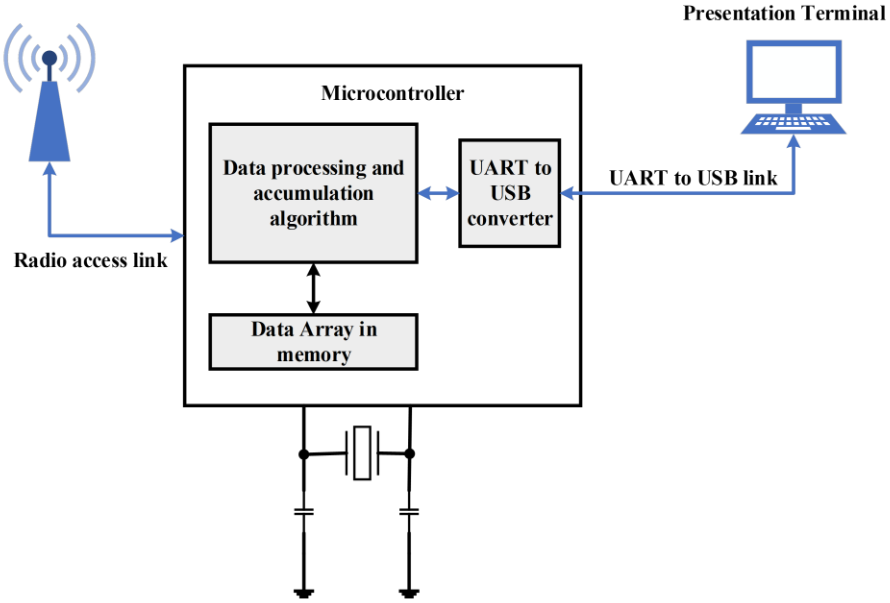

Figure 6b: Remote Node (RN)

Figure 7a: Testbed implementation

Figure 7b: Sensors installation

Figure 7c: Cased Node

remotely through wireless communication between the SNs and the RN. The data are displayed on a PC connected to the RN for presentation in a Microsoft Excel spreadsheet with the aid of Parallax Data Acquisition (PLX-DAQ) add-in software (PLX-DAQ, 2021). An abridged result of the data received is shown in Table 1.

Table 1: Results from SN 1, 2, 3 and 4

Start Time (Sec)	P1 (Pa)	P2 (Pa)	P3 (Pa)	P4 (Pa)	F1 (m^3/s)	F2 (m^3/s)	F3 (m^3/s)	F4 (m^3/s)	T1 (K)	T2 (K)	T3 (K)	T4 (K)
0.1	2413.17	2413.17	2413.17	2413.17	0.076	0.076	0.076	0.075	311.65	311.65	311.65	311.65
0.4	2413.17	2413.17	2413.17	2413.17	0.076	0.076	0.076	0.076	311.65	311.65	311.65	311.65
27.7	2413.17	2413.17	2413.17	2413.12	0.076	0.076	0.076	0.073	311.94	311.94	311.94	311.94
28.7	2413.17	2413.17	2413.17	2413.00	0.076	0.076	0.076	0.072	311.94	311.94	311.94	311.94
98.5	2413.17	2413.17	2413.17	2413.17	0.076	0.076	0.076	0.076	312.00	312.00	312.00	312.00
99.4	2413.17	2413.17	2413.17	2413.17	0.076	0.076	0.076	0.076	312.00	312.00	312.00	312.00

At the start-up time of the pump, the sensor nodes were not activated to take readings until the pump was fully running and steady and all valves closed. The SN readings were started at a pressure of 2413.17 Pa, flowrate of 0.076 m^3/s and a temperature of 311.65K respectively as shown in Table 1.
With valve 1 (located directly behind SN4) open, a significant drop in pressure from 2413.17Pa to 2358.00Pa and flowrate drop from 0.076m^3/s to 0.070m^3/s were observed on SN4 as shown in Figure 8 and Figure 9 within 3 seconds. These values were maintained for 36sec until valve 1 was closed and the pressure and flow rate returned to 2313.17Pa and 0.076m^3/s within another 3 seconds.

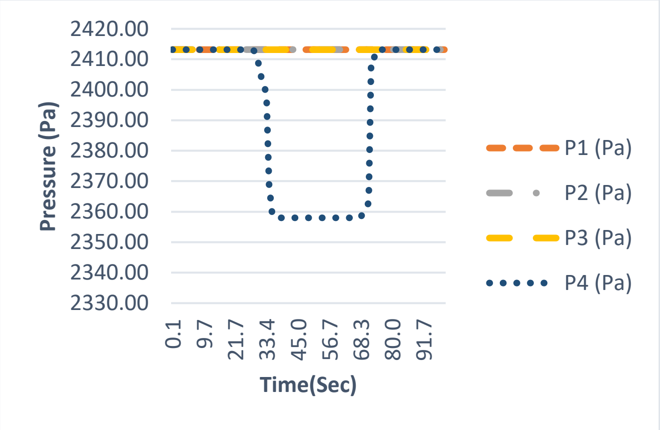

Figure 8 Pressure simulation at Valve1

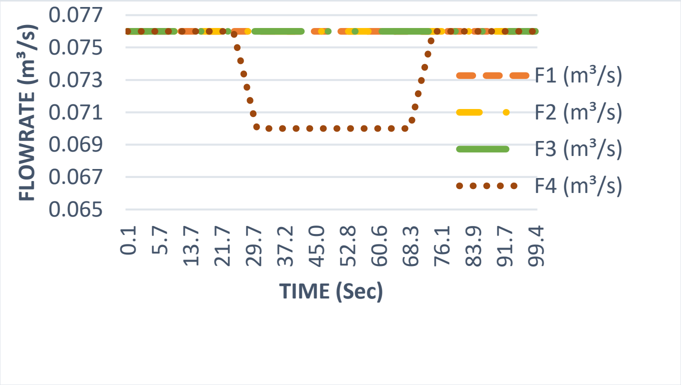

Figure 9 Flowrate simulation at Valve1

In Figure 10 and Figure 11, it is shown that when valve 2 is opened (which is located between SN 1 and 2) a drop in pressure from 2413.17Pa to 2358.00Pa and flowrate from 0.076m^3/s to 0.070 m^3/s were observed on SN2. This concurrently had an effect in SN 3 and 4 as the pressure and flow rate are seen to have equally dropped from 2413.17Pa to 2370.00Pa and from 0.076m^3/s to 0.072m^3/s respectively. When Valve 2 is closed gradually, there was a quick rise in pressure and flow rate to its initial state within 3 seconds interval of time. The pressure and flow rate of SN1 remains unchanged when valve 2 is opened because the SN1 is located behind valve 2. Valve 1 and Valve 2 when opened, diverted some of the fluid flow to the reservoir as an alternate route based on the testbed design to avoid oil spill on the soil.

With the rapid pressure and flow changes observed, it is clear that any changes in the pipeline operations can be quickly noticed and appropriate actions are taken.

Temperature readings from SN1 to SN4 show a steady temperature reading of 311.95K for about 62min. After a 1-hour interval from the start time, the flowing fluid temperature rose from 311.95K to 312.00 K as indicated in Figure 12. A steady temperature of 312K was then recorded on the four sensor nodes. This temperature change is attributed to a change in environmental temperature due to the sun's intensity as at the time of data collection.

A. Accuracy

Eqn. 6 expresses the percentage accuracy in the data acquisition system using the experimental testbed.

$$Percentage\ Accuracy = \frac{Actual\ Value\ Read - Expected\ value}{100}\% \qquad (6)$$

Pressure different at SN2 = 55.17Pa, Flow rate difference at SN2 = 0.006m^3/s

Pressure different at SN3 = 43.17Pa, Flow rate difference at SN3 = 0.004m^3/s

At a pressure change of 12Pa from SN2 to SN3, the expected flow rate is 0.0047m^3/s resulting in a percentage accuracy of 0.07%.

B. Response time performance

The response time of the system can be calculated as:

$$Response\ time = SN\ throughput + n \times transmission\ latency \qquad (7)$$

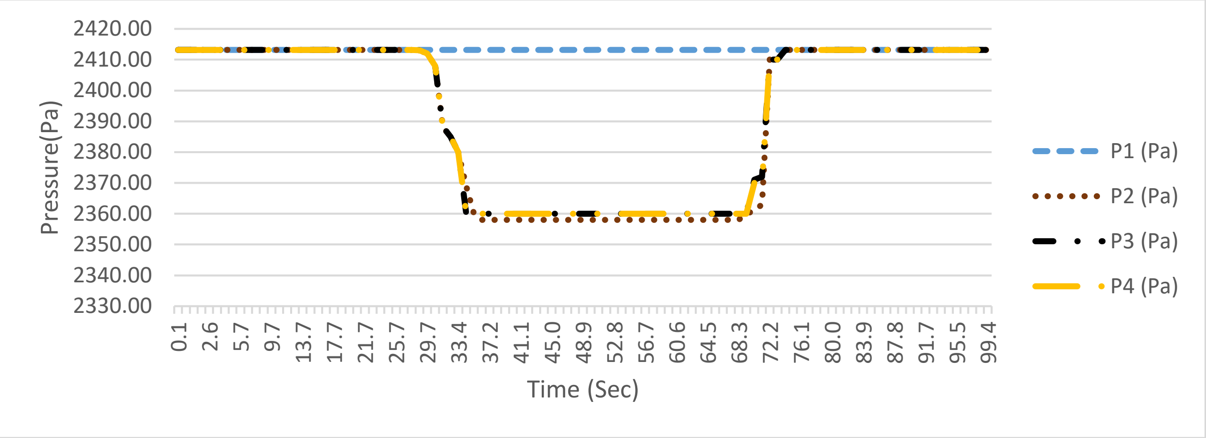

Figure10 Pressure simulation at Valve 2

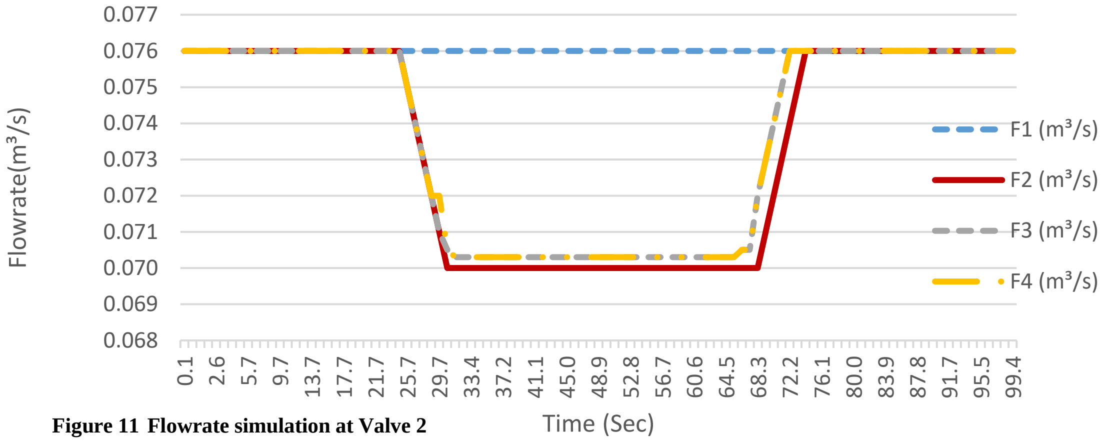

Figure 11 Flowrate simulation at Valve 2

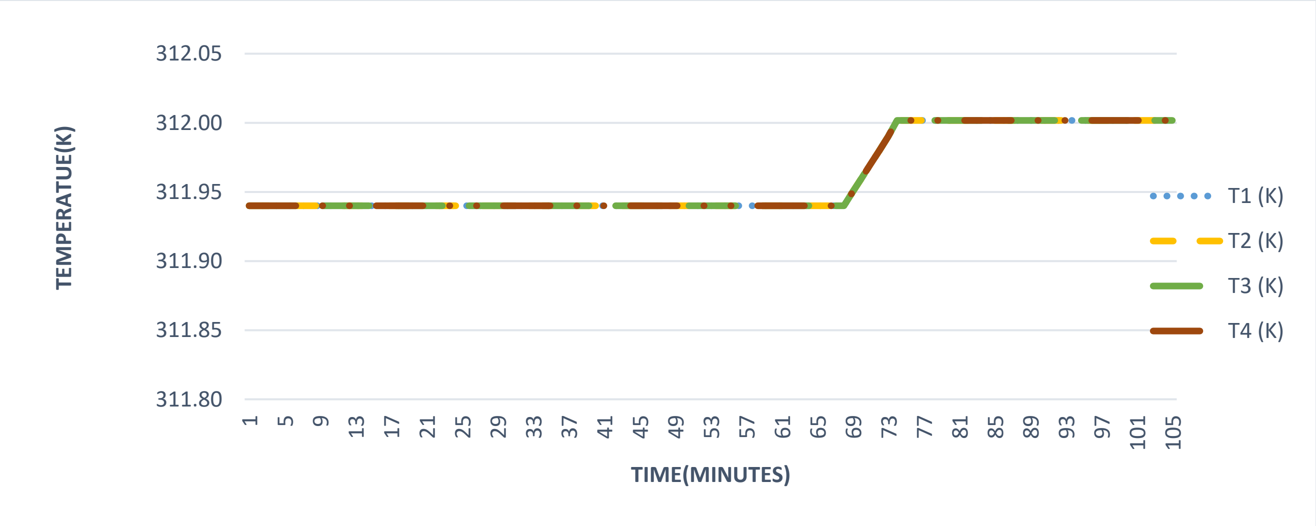

Figure12 Temperature analysis of pipeline

Where n is the number of SN repeaters from the parameter sensor to the RN.

At a transmission frequency of 2.5GHz and data rate of 250kbps, the latency within 1km is negligible and the response time as it is in this simulation will approximate the SN throughput ($\approx 3sec$). However, at larger distances, the network will expand and the latency may become significant as more SN repeaters will be needed.

SN throughput = total sensor throughput + processing time + radio throughput

$$= 3sec + 10\mu sec + 170\mu sec = 3.00018sec$$

Each SN system throughput is 3.00018sec and the radio transmission latency is 70msec.

Using Eqn. (7), the response time of the system for direct SN to RN communication is 3.07018sec in a range of 1km. This result shows that WDAS has a better response time performance compared to existing data acquisition systems discussed in Adegboye *et al.* (2019), Febaide & Uzedhe (2021) and Aibinu *et al.*, (2021) as shown in Table 2.

Table 2: Response time performance of data acquisitions systems

Data Acquisition method	**Response time**
Biological method	180 minutes
Supervisory method (SCADA, DCS, WSN, IoT)	9.4 minutes (average)
Remote sensing	157.5 minutes
WDAS	3.07018sec

V. CONCLUSION

The study provides the feasibility of using low-cost wireless devices for data acquisition in remote pipeline networks. The experiment clearly shows a relative drop in flow rate with pressure drop at an error margin of 0.07%. With the achieved response time of about 3.0sec, the marginal error is minimal and indicates good accuracy. Owing to the high cost of implementing existing data acquisition systems in the oil and gas sector, WDAS as a new method can be looked into as an alternative solution for the management of oil and gas pipeline infrastructure due to its cost-effectiveness and fast response time.

AUTHOR CONTRIBUTIONS

I.C Febaide: conceptualization, methodology, system simulation and testing, software, writing, **G. O. Uzedhe:** methodology, writing- review &editing, system simulation and testing, supervision.

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