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Design of an IoT System for Strain Measuring in Steel Structured Bridges

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Abstract – *In recent decades bridges have become an important economic icon in public and industrial transportation. As the condition of a bridge decides the safety of the users, continuous monitoring of structural condition is vital and it helps to establish an efficient transportation. Moreover, efficient measuring techniques help to make powerful decisions of its environment. Presently, the majority of railway bridges in Sri Lanka are steel structured bridges. Strain, vibration and movements measurements are the critical parameters used for measuring the condition of these steel structured bridges. Among them, strain monitoring plays a major role in determining the condition of bridges. Though strain gauge-based monitoring systems are being used for monitoring of strain, present monitoring practice in Sri Lanka is limited to analysis of pre-captured and stored strain data. This technique is obsolete and is associated with many drawbacks. Thus, we propose a continuous condition monitoring internet of things (IoT) system for steel railway bridges which directs to analysing the data online, hence having a better reliability. Through this design, a total integrated solution has been introduced to measure and analyse online strain data and to make fast decisions by the experts.*

***Keywords**: Steel Structured Bridges, Strain Monitoring, Wireless Sensor Networks (WSNs), Internet of Things (IoT)*

1 INTRODUCTION

The transportation network of a country is one of the crucial factors, which has a direct impact to the country's economy. Services like transportation of raw material and then return with the products from the factories, passenger services etc. totally depend on the quality of the transportation network. Abreast of the time, due to the low maintenance of these infrastructure, they may be in a poor condition. Nevertheless, a simple accident caused due to poor conditioned transportation infrastructure may cause a serious loss even ranging to the loss of thousands of human lives. Therefore, conditions monitoring schemes of the transportation infrastructure are vital. On the other hand, the proper maintenance of the transportation infrastructure can be considered as a future investment to the country. When considering the efficiency of the transportation structures, bridges play an important role. Therefore, optimum conditions of the bridges are needed to be maintained for a safe and an efficient transportation. To maintain the optimum conditions throughout, bridges have to be designed together with good health monitoring mechanisms.

Presently, in Sri Lanka, the wired, manual monitoring systems are being used to monitor conditions of steel bridges [1]. Furthermore, the data is analysed offline. Here, a severe problem arises when the decisions with less accuracy are being obtained through this system due to the obsolete and less accurate data, which has been obtained manually by the technical persons.

Therefore, considering the aforementioned circumstances, a wireless sensor network is introduced to overcome the above issues. Wireless sensor network is a dedicated sensor group which is networked with wireless communication infrastructure to gain some specific data without a human interference [2, 3]. The data is gathered, may be for monitoring purpose or may be to actuate some specific actuators.

In this paper, the strain is taken as the measured parameter of the system and the total sensor node consists of two major parts, namely the transducer and the communication unit.

The current manual strain monitoring system used in Sri Lanka is a wired monitoring system [1], which is consisting of a strain sensor element, data processing and acquisition unit (data logger) and the condition evaluation/decision making system. The sensor element is typically linked to copper cables. This traditional system is very expensive and when using for monitoring from a long-distance communication, most of the time it may be susceptible to disturbances. Another drawback of this system is that it doesn't possess any data encryption mechanism. As a solution, we present the design of a wireless sensor network (WSN) based internet of things (IoT) system for measuring strain in steel railway bridges.

The rest of the paper is organized as follows. Section 2 further discusses the currently available WSN based monitoring systems around the world. In Section 3, we present the proposed IoT strain measuring system. In Section 4, we further elaborate on the functionality of the proposed strain measuring system followed by the prototype implementation details and the testing results. Finally, Section 5 concludes the paper highlighting several future research avenues.

2 WSN-BASED MONITORING SYSTEMS

There are a number of bridge strain monitoring systems employed around the world. In the system of [4], an accelerometer is deployed for strain monitoring and the accelerometer reading is taken over the three directions XYZ. Here the accelerometer reading is further enhanced by a signal conditioner. Eventually it is transmitted via a wireless module. Through this method, acceleration parameter values can be directly obtained and those parameters can also be directly used to calculate the strain. It also helps to monitor the movements of the bridges. Nevertheless, its durability is comparatively low compared to strain gauges. Moreover, it uses complex mathematical calculations when determining strain values from the data collected at a particular node [4].

To overcome the above mentioned drawbacks, a wireless strain monitoring system for raw strain measurement is proposed in [5]. This system consists of a micro-electromechanical system, which has an inbuilt data processing unit within the same sensor elements. This consumes a very low power and provides high efficiency as the on-board microprocessor of the wireless sensor can facilitate an efficient distributed data processing in real time. Furthermore, its durability is high as it uses fiber optic strain measuring sensors.

In general, even the bridge monitoring systems as in [5] have to overcome many challenges as listed below.

As the fact that strains of a bridge is generally small, sensor output signal would also be in a very small scale of Volts. Therefore, small fluctuations of the signal is needed be detected by the signal processing unit. Meantime, high resolution of the sensor plays a vital role. On the other hand, when a locomotive is moving on a bridge, it causes to vary the strain continuously. In order to capture the corresponding sensor output voltage variation, high frequency processing system is needed. Generally the railway bridges are in high noisy environments, hence the signal to noise ratio at the sensor output needs to be improved. Another crucial requirement of the sensor node is the high speed data processing and transmission. Processed data should be transmitted with a high speed. Due to the low power availability at the sensor, it cannot maintain a large buffer or memory to store processed data. At the same time, nowadays, low-power radio transceivers provide a limited bandwidth (a maximum of 250 kbps in the case of IEEE 802.15.4 networks). Time synchronization is also a crucial factor in WSNs. Since each sensor node has its own time clock, sensor and relay nodes must be synchronized with each other, in order to eliminate phase delays.

To overcome all the aforementioned challenges and to cater for all these requirements, in this research we propose a reliable and efficient WSN based strain monitoring IoT system for steel structured railway bridges, which is much superior over the systems in [4, 5] .

3 DESIGN METHODOLOGY

The proposed WSN based IoT steel bridge monitoring system consists of several important sub units. Amongs them the most vital is the wireless sensor network and its nodes which captures the distributed strain measurements. The structural construction of a sensor node is depicted in Figure 1.

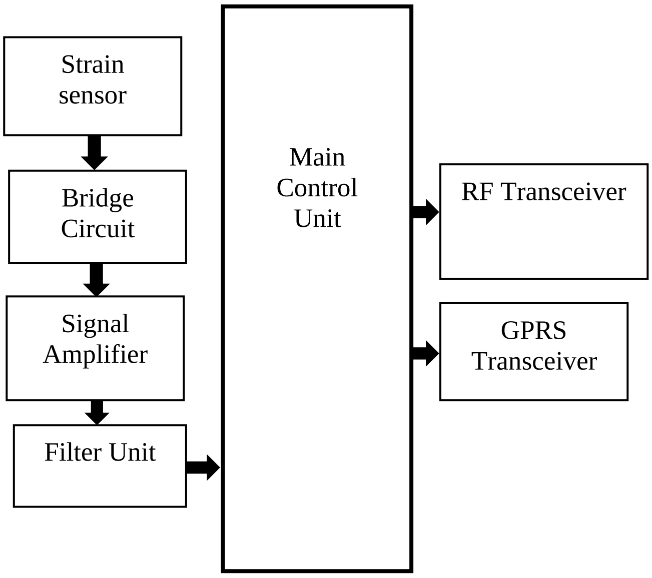


Figure 1: System block diagram of a sensor node

As mentioned earlier, in this design strain is the measured parameter, strain gauge is used as the sensor element which is effectively a variable resistor whose resistance varies with the strain applied. Sensor node is consisted of several sub units including sensor element, filter unit, signal conditioning unit, ADC and processing unit. When a strain is applied on the strain gauge, it changes its resistance which in-turn creates a voltage difference at the bridge output. This output voltage difference is directly proportional to the change of the variable resistance in the strain gauge, hence to the strain applied.

3.1 Sensor Element and Wheatstone Bridge Circuit

A strain gauge of 10mm was selected as the sensor element due to its considerable resistance change possible, the temperature factors and also its availability. Here, the sensor element shown as R5 is converted in to a transducer by plugging in to a one branch of the Wheatstone bridge [6]. In order to reduce the current flow through the branches of the bridge, an additional resistor R1 was attached as shown in figure 2.

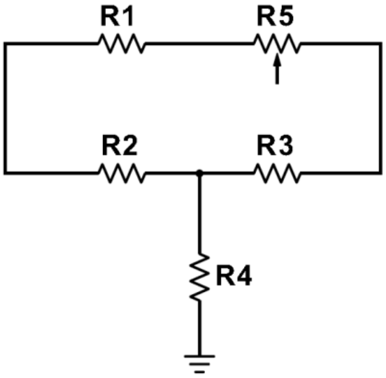


Figure 2: Basic sensor element placement in a Wheatstone bridge

The calibration and the scaling were carried out using (1) [6].

$$\frac{V_O}{V_{ex}} = \frac{GF.\varepsilon}{4}\left\{\frac{1}{1+GF.\varepsilon/2}\right\} \qquad \text{--------(1)}$$

Where,

$\boldsymbol{V_o}$- Sensor output signal.

$\boldsymbol{V_{ex}}$- Input voltage of the bridge.

$\boldsymbol{GF}$- Gauge factor of strain gauge.

$\boldsymbol{\varepsilon}$- Strain.

The gauge factor can be calculated as (2).

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon} \qquad \text{--------(2)}$$

It is very important to note that the calculated parameter values and the measured values of GF may slightly change due to the temperature coefficient of the strain gauge and due to the physical condition of the resistors. In this work, we obtain the GF value through calculations.

3.2 Amplifier Unit

As stated earlier, the voltage difference at the Wheatstone bridge output is directly fed to the amplifier unit. INA 114 instrumentation amplifier [7] was selected as the amplifier unit as it consumes very low current and also due to its law noise amplification capability. Moreover, it supports an input signal with high impedance and produces an output with low impedance.

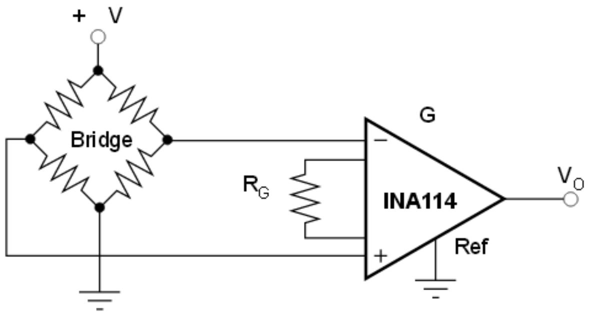


Figure 3: INA 114 low noise amplifier connection to bridge output

3.3 Filter Unit

It is important to note that the sensor node has to work in a very noisy outdoor environment. On top of that, the output of the transducer is usually a few millivolts. Therefore, noise can be easily added to the signal and distort the output. Therefore the transducer output is first amplified. In order to filter out the noise in the captured signal, an active low pass filter was used after the amplifier output.

Another important aspect is the stability of the filter unit, which totally depends on the quality of the passive elements. In this work we design the unity gain filter using MCP601 low noise operational amplifier [8]. Cut-off frequency can be adjusted by varying the resistor and capacitor values in the circuit of Figure 4. Note that one of the demarcating features of this filter unit is, it is an anti- alliancing filter, which directly helps to filter out the noise.

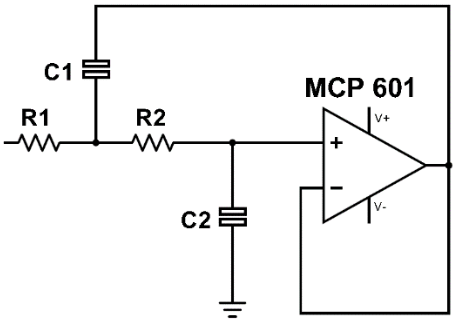


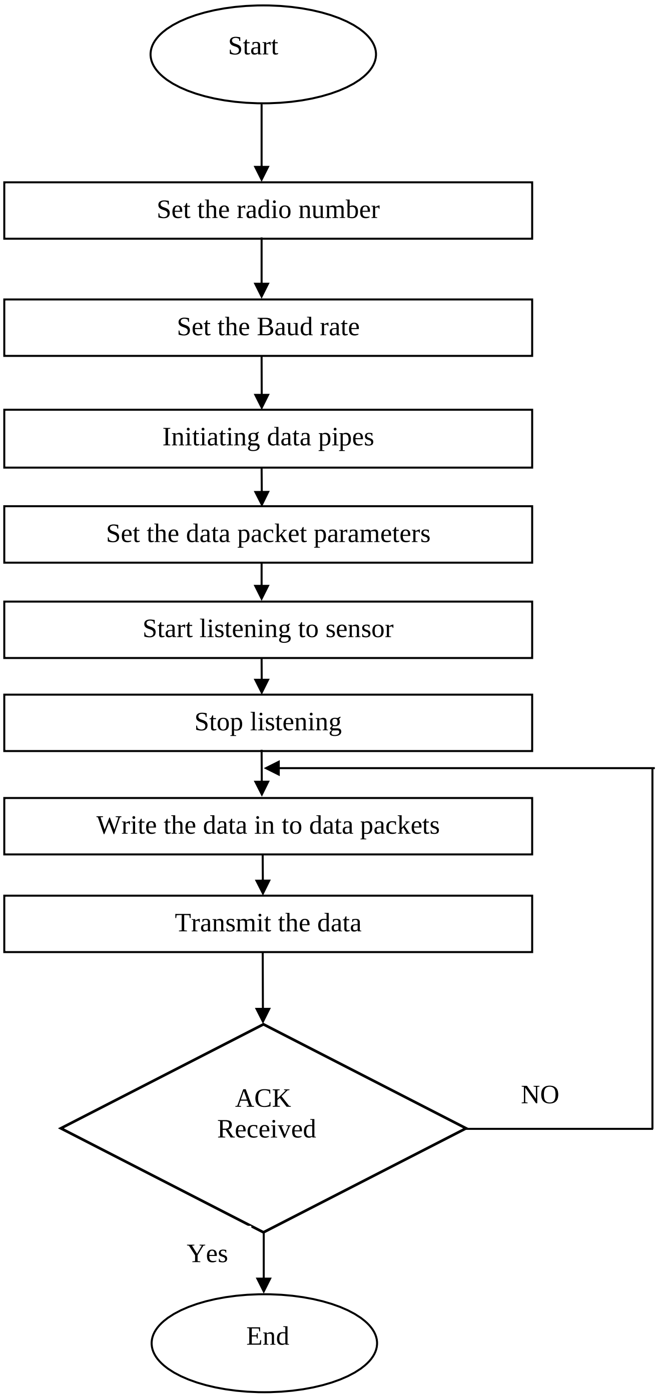
Figure 4: Active low pass filter topology

3.4 Analog to Digital Convertor (ADC) and Processing Unit

ARDUINO UNO microcontroller board was employed as the main signal processing unit. This controller consists of a ten bit in-built ADC. Therefore, a $\frac{1}{1024}$ digital resolution is provided by the ADC.

3.5 Basic Architecture of the Wireless Sensor Network

The basic system architecture of the network model consists of two major sub systems namely, sensor network and the server network. In the sensor network, the sensor nodes capture the strain values at each point and relay these data to a central node which we name as master node. The sever network consists of the master node and the linkage to the external remote networks in point-to-point mode. We use radio frequency (RF) communication for the sensor network while using general packet radio service (GPRS) based communication in the server network. The operating algorithm of Sensor nodes is depicted in figures 5 and 6. Also, figure 7 presents the communication algorithm for the master network.



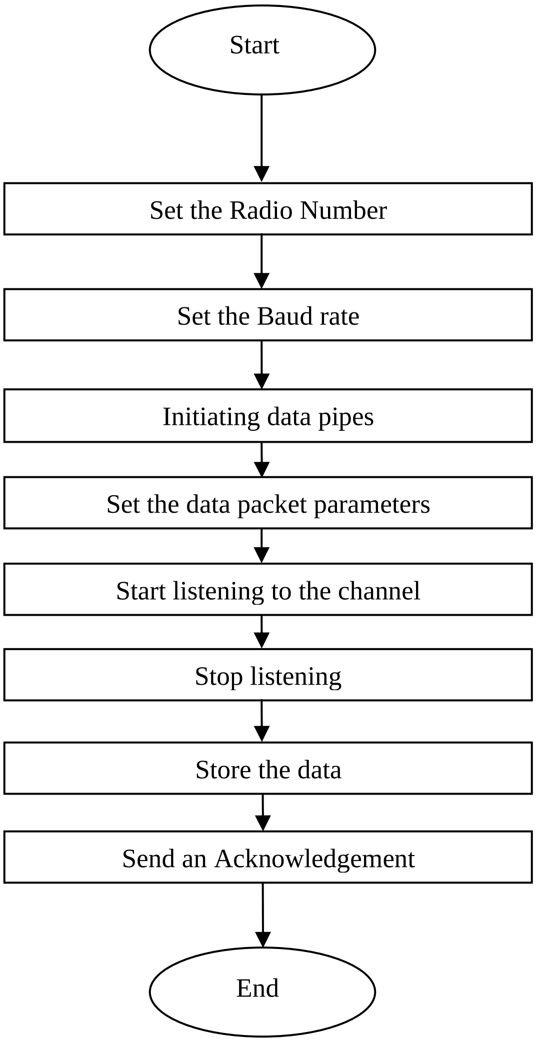


Figure 6: RF communication algorithm (Receive)

Figure 5: RF communication algorithm (Transmit)

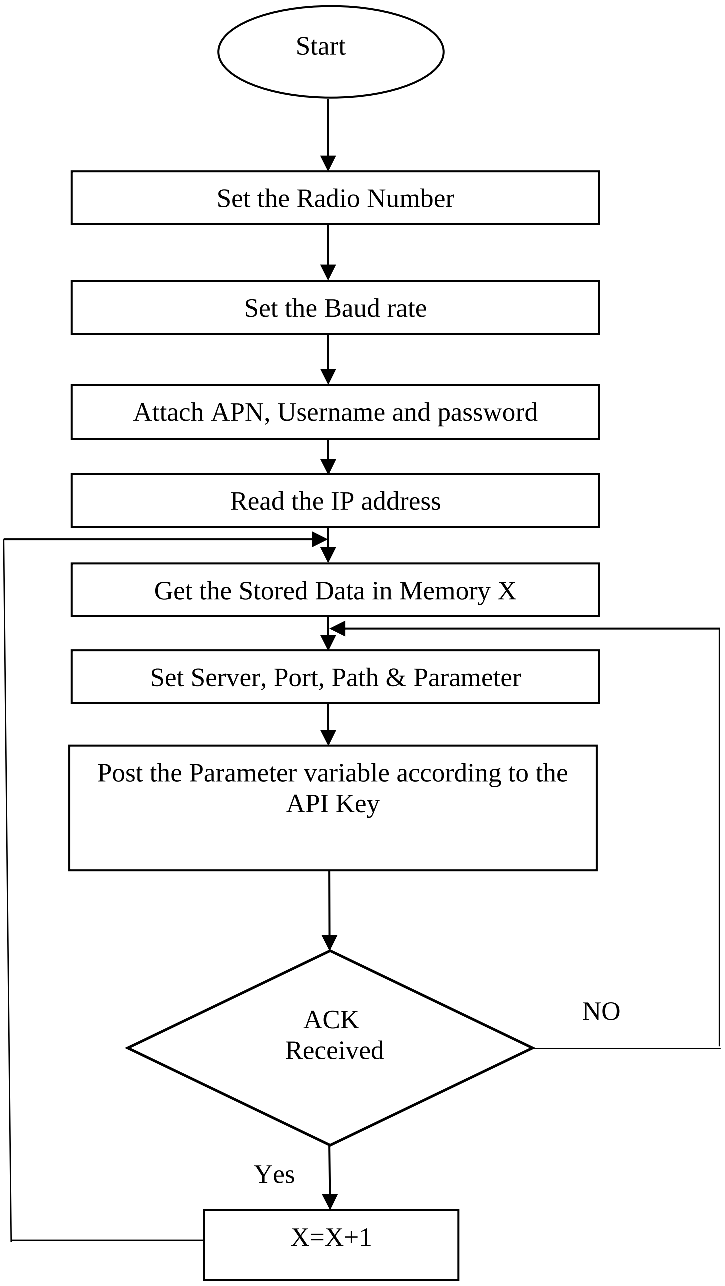


Figure 7: Master network communication algorithm

Recall that, master node to server communication is established through GPRS communication. One of the major advantages of using GPRS is the ability to achieve non-line of sight, long distance communications. The real time data which is obtained by the sensor network is ultimately transferred to an IoT server. Here the THINGSPEAK IoT server is used for that particular test implementation process. Figure 8 depicts the data reception and storage at the master node.

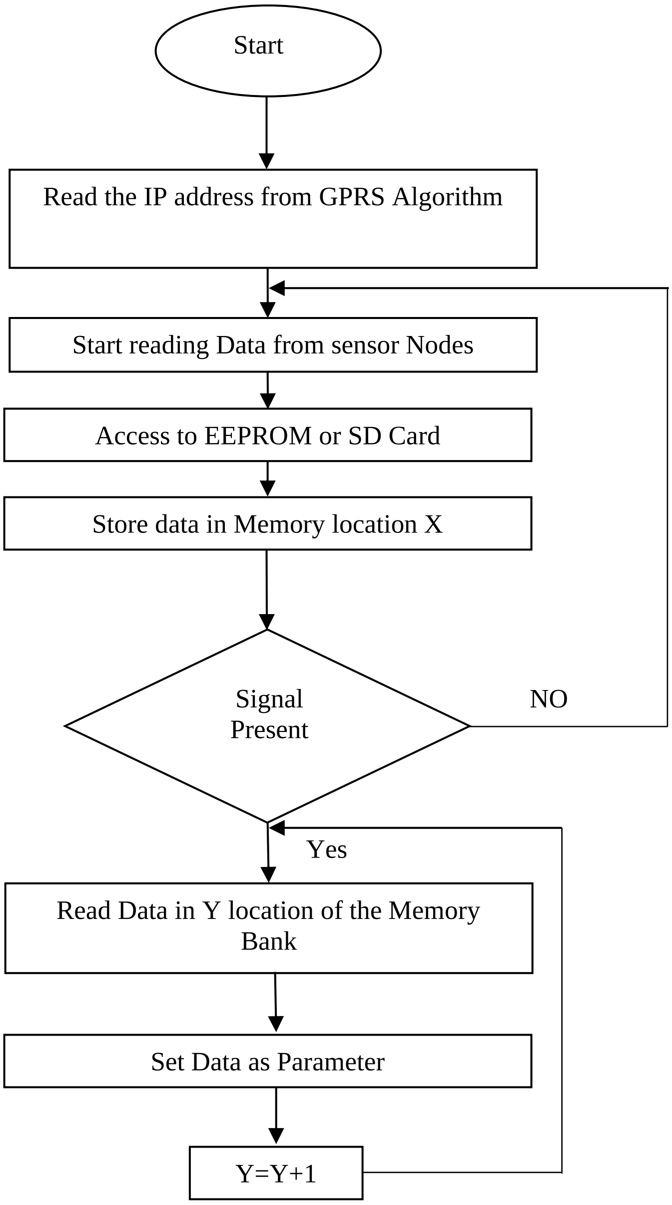


Figure 8: Data storage algorithm

5 OPERATION, PROTOTYPE IMPLEMENTATION, TESTING AND RESULTS

The overall system architecture is illustrated in figure 9. As mentioned earlier, THINGSPEAK IoT server is used to facilitate a graphical user interface (GUI) at the remote server. Trend of the strain pattern can be easily visualized and strain data can be downloaded in excel format for further analysis using the data available at the IoT server.

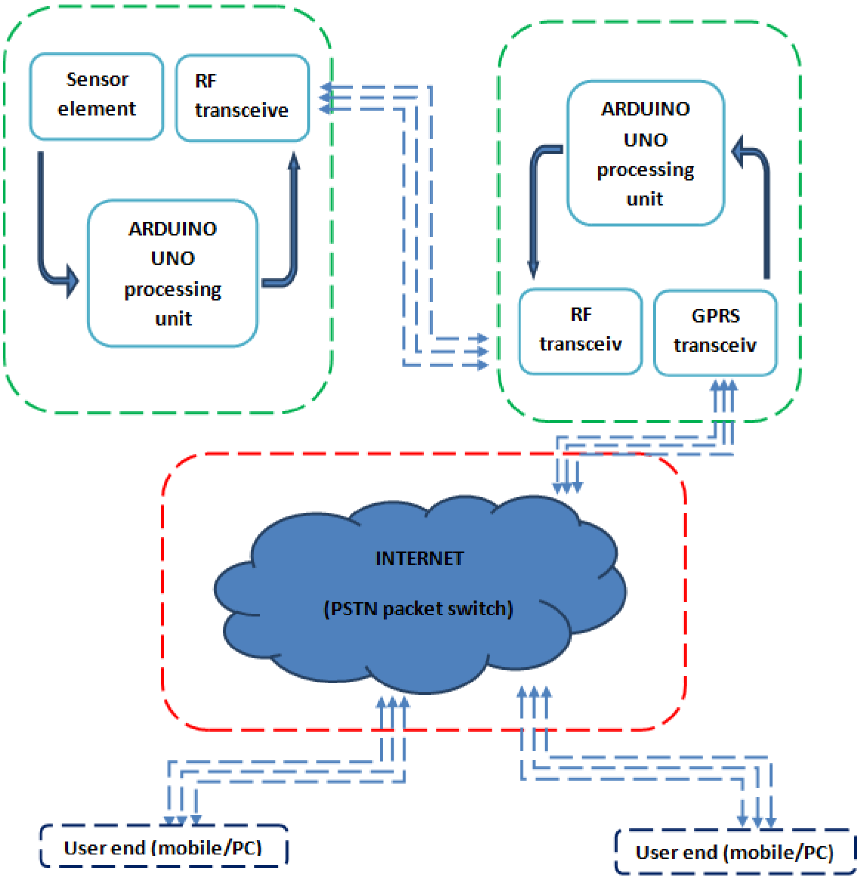


Figure 9: Overall System Architecture

A prototype system was implemented and initially the response of the sensor element was obtained by varying the load, in order to check its linearity. Table 1 shows the output voltage value of the sensor versus the applied load to cause strain. Graphical representation in Figure 10 clearly depicts a linear behavior.

Table 1: Sensor Element's Linearity Test

Load (kg)	V_{out} (mV)
0	0.912
20	0.990
30	1.032
40	1.074
50	1.112
75	1.210
100	1.311
125	1.414
150	1.513

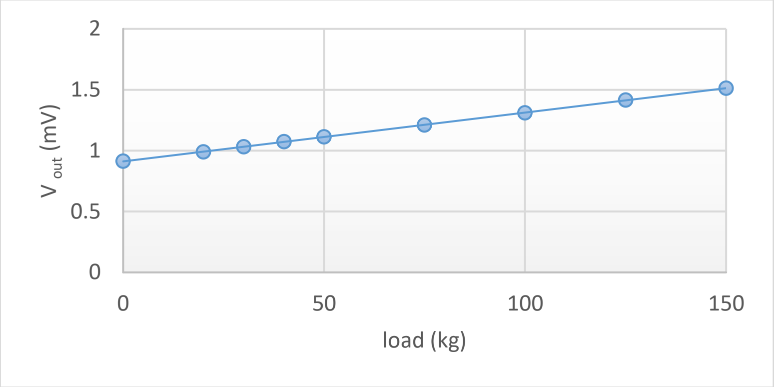


Figure 10: Linearity of the Sensor

Another test was performed to determine the effect of interference signals at a sensor node, especially present when a metal train moves over the railway track. The interference test was done under the effect of minimum magnetic field. The tabulated data for the interference test is shown in the figure 11. Number of data received was taken through the mean value of three different attempts. An optimum condition for maximum data receiving was obtained at 9600 baud rate with 100ms delay between two data sets. The correctly received number of data packets is a clear indication of the effect of external interference. Thus, we can conclude that even under interference, data packets can be effectively transmitted at very high data rates maintaining more than 50% success rate. Moreover, transmitting at lower rates and larger accepted delay times can yield higher success rates exceeding 75%. This is very much adequate for our IoT system application.

Table 2: Interference Test data

No. of data in data set	Delay time (ms)	Baud rate	No of data received
100	1000	115200	51
100	100	115200	55
100	10	115200	50
100	1000	9600	81
100	100	9600	96
100	10	9600	77
100	1000	4800	67
100	100	4800	76
100	10	4800	69

It is also worth to investigate the maximum separation between the nodes in the WSN to maintain an effective relaying of data packets generated at each sensor node, amidst all interference. Table 3 tabulates the RF communication data in the presence of a S12 locomotive engine's interference. Here, the number of data received was obtained through the mean value of three different attempts. It can be observed that the optimum distance in-between the two sensor nodes to have a sufficient success rate, is around 2.5m.

Table 3: RF Data near the S12 locomotive engine

No. of data in the test set	Distance between two sensor nodes(m)	No. of data received
100	3	58
100	2.75	64
100	2.5	78
100	2	79
100	1.75	80
100	1.5	84
100	1.25	87
100	1	86

Moreover, another test was carried out to determine the success of the server network communication under the created electromagnetic interference, due to the moving locomotive engine. The test results are tabulated in Table 4, under different baud rates. It is clear that the communication achieves a success rate exceeding 95%.

Table 4: GPRS Test Data

No. of data	No. of connection failures	ACK failures	Baud rate	No. of data received to server
50	2	3	115200	48
50	3	1	115200	49
50	1	1	115200	49
50	6	2	115200	44
50	1	2	9600	48
50	1	2	9600	49
50	2	0	9600	48
50	1	1	9600	49
50	2	0	4800	48

Furthermore, figures 11 and 12 show the graphical display of data in the web interface of the THINGSPEAK IoT server.

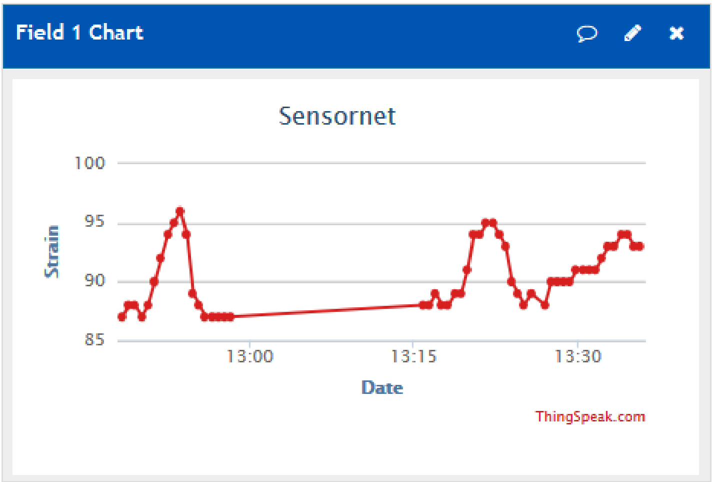


Figure 11: The graphical representation of the Strain

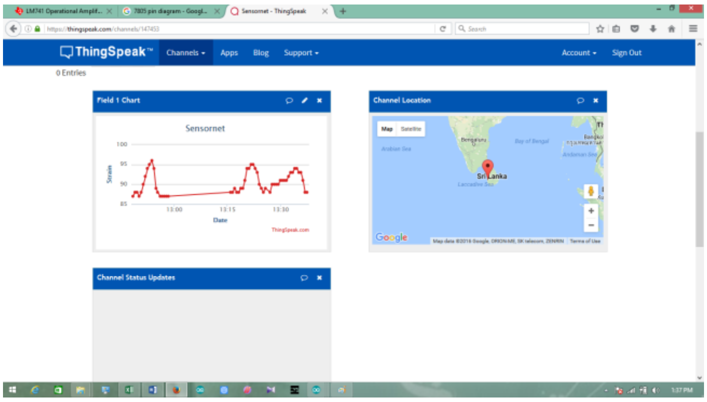


Figure 12: Graphical User Interface

6 CONCLUSION AND FUTURE WORK

Nowadays, IoT has become a vital platform, which provides an easier approach to bring loads of information to one’s fingertips. If a technical personnel can access the strain data of steel structured bridges, measured via the proposed IoT system from anywhere in the world, that would be a huge advantage for minimizing the bridge infrastructure failures. Therefore, it directly helps to increase the total productivity and also to enhance the safe transportation conditions.

This research basically focused on enhancing the condition of steel structured bridges in Sri Lanka. Furthermore, it is introduced as an IoT product of low cost, long life and with minimum maintenance.

Design and implementation of hardware to withstand extreme environmental conditions was beyond the scope of this work, hence we categorize the same under future work.

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