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A Remotely Deployable Wind Sonic Anemometer

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Abstract:

Communication and computing shape up base for explosion of Internet of Things (IoT) era. Humans can efficiently control the devices around their environment as per requirements because of IoT, the communication between different devices brings more flexibility in surrounding. Useful data is also gathered from some of these devices to create Big Data; where further analysis assists in making life easier by developing good business models corresponding to user needs, enhancing scientific research, formulating weather prediction or monitoring systems and contributing in other relative fields as well. Thus, in this research a remotely deployable IoT enabled Wind Sonic Anemometer has been designed and deployed to calculate average wind speed, direction, and gust. The proposed design is remotely deployable, user-friendly, power efficient and cost-effective because of opted modules i.e., ultrasonic sensors, GSM module, and solar panel. The testbed was also deployed at the roof of Computer & Information Systems Engineering (CIS) department, NED UET. Further, its calibration has been carried out by using long short-term memory (LSTM), a deep learning technique; where ground truth data has been gathered from mechanical wind speed sensor (NRG-40 H) deployed at top of Industrial & Manufacturing (IM) department of NED UET. The obtained results after error minimization using deep learning are satisfactory and the performance of designed sensor is also good under various weather conditions.

Keywords: *IoT, Big Data, Anemometer, LSTM.*

1. Introduction

Anemometer is a device that is used to measure wind speed and direction. It is a core component, of weather station, for monitoring and analysis of air quality. It is used for wind turbine control, air flow measurement and observation in tunnel, airports, and chemical plants. The sensed data by this sensor can also be used to predict storms to generate alert for governments, help engineers and climatologists. Aerodynamic effects on cars and ballistic missiles are also important set of parameters for engineers to develop efficient design. Apart from this, wind speed and direction are few of the key factors behind growth of crops. Therefore, with the help of real time data gathered from anemometers, an expert system for agriculture sector can be trained which makes decision in real time. Hence, automation in agriculture sector can be introduced which ultimately leads to efficient utilization of precious resources i.e., water and improvement in overall food quality and quantity.

In literature, different types of anemometers i.e. cup anemometer, vane anemometer, ultrasonic anemometer, laser Doppler and hot-wire are available [1] - [6]. Vane and cup anemometer are mechanical type and mostly used on commercial scale because they are known for ages [1]. However, due to dependency of vane anemometer on mechanical gears their life time is less. They need constant maintenance because dust particles in air jam the gears and affect its accuracy, especially during wind gusts and lulls. That is why ultrasonic anemometers are preferred, to calculate wind data and capture

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gusts and lulls properly, because there is not any involvement of physical moving parts.

Word ultrasonic basically refers to speed of sound, Thus it is clear that ultrasonic anemometer calculates wind speed and direction with the help of sound waves generated through transducers. Various designs and mathematical formulation are available in literature for design of ultrasonic anemometers each having different set of pros and cons. In [2] an ultrasonic anemometer with three piezoelectric transducers has been used to form a rectangular tetrahedron, along with phase meter coupled with receiver to calculate wind velocity. However, in extreme weather condition this design does not give satisfactory results. The proposed solution in [2] also causes air turbulence in the wind, thus reducing further accuracy. However, a modified design proposed in [3], with three transducers forming a horizontal equilateral triangle minimizes this turbulence of wind through its frame. Yet, in [3] the effect of temperature and humidity on ultrasonic waves was not eliminated completely. Therefore, in [4] ultrasonic anemometers with four transducers were used to eliminate the effect of temperature on ultrasonic waves. Transducers were also operated in low frequency and average of wind velocity was also taken to attain good accuracy especially in frost. This four-transducer orthogonal design, proposed in [4], is recognized as 2D ultrasonic anemometer. A 3D ultrasonic anemometer in [5] provides less aerodynamic turbulence by having complex design and mathematical equations. However, the design and implementation of ultrasonic anemometer mentioned is still very expensive. Recently, a new type of solution has entered anemometry world called Laser Doppler Anemometer [6] in which wind velocity components are calculated through the Doppler shifts, wind produces in laser rays but this anemometer is still not commercially available. In [14] an innovative ultrasonic anemometer has been designed for marine applications and calibrated using wind tunnel, however, authors have used deep learning for calibration. In [15] another low cost ultrasonic anemometer is designed using FPGA.

In terms of accuracy ultrasonic anemometers are far better than vane anemometers because no physical moving part is present. However, cost of ultrasonic anemometer varies between US $1500 and US $2500 which makes them difficult to function on commercial scale. That is why, a cost-effective solution has been proposed [7], as an initial study of the research proposed in this paper. In [7], three different design models of ultrasonic anemometer have been presented and final solution has been tested extensively by deploying testbed at Computer and Information Systems Engineering Department of NED UET for over week duration. Data collected from it has been compared with NRG-40H cup anemometer deployed at Industrial and Manufacturing Engineering Department of NED UET. It has been justified, through comparisons, that results obtained by designed sensors are satisfactory. Furthermore, calibration of designed ultrasonic anemometer has also been carried out using simple machine learning techniques. Although, the solution proposed in [7] was based on Internet of Things (IoT) technology and providing direct link to cloud through Wi-Fi communication link. However, it was powered through direct power source which was a major drawback since at remote locations IoT enabled devices need to be power efficient and self-rechargeable as well. Apart from that, at remote locations, especially in Pakistan Wi-Fi communication is hardly available. Thus, from commercialization point of view, in this research the authors have proposed a modified solution of one presented in [7] by integrating additional features i.e., solar panel, battery, general packet radio service (GPRS) module which makes it possible to be deployed at any remote location for long period of time. Apart from that, final design has been properly cased with the help of fiber base frame for maintaining better line of sight (LoS) communication between ultrasonic sensors and their fine operation in harsh or rainy weather conditions. Enhanced machine learning techniques have also been exploited for calibration of final design. The cost of this enhanced design for anemometer is around US $60 which is extremely low as compared to existing solutions [1] - [6]. It is unique in its kind with eight pillars supporting four transmitters and receivers of HC-SR04 sensor and makes it one off the cheapest ultrasonic anemometer.

2. Sensor Design

Three different designs models of ultrasonic anemometer and analysis of their accuracy with respect to mathematical equations have been presented in [7]. Basic principle is to consider the effect of wind velocity on the speed of sound waves generated by ultrasonic sensors in different directions. A wind velocity component in the direction of the propagation of sound supports the speed, thus leading to an increase in it but decrease in duration and vice versa. Thus, different wind velocities provide different propagation times at fixed distance between sensors. This change in duration of speed of sound is inversely proportional to the speed of wind. Analysis and pros and cons of each design have been discussed in [7] with details. Equations for calculating wind speed and direction are as follows.

$$V_x^{wind} = \frac{d_{TR}}{2} * \left(\frac{1}{t_1} - \frac{1}{t_2}\right) \quad (1)$$

$$V_y^{wind} = \frac{d_{TR}}{2} * \left(\frac{1}{t_3} - \frac{1}{t_4}\right) \quad (2)$$

$$V^{wind} = \sqrt{{V_x^{wind}}^2 + {V_x^{wind}}^2} \quad (3)$$

$$\theta = \left(\tan^{-1} \frac{V_y^{wind}}{V_x^{wind}}\right) \quad (4)$$

Equation (1) and (2) are used for measuring horizontal and vertical component of wind velocity. d_{TR} is distance between transmitter and receiver, t represents time-of-flight (tof) calculated by respective HC-SR04 sensors and V^{wind} in (3) is speed of wind.

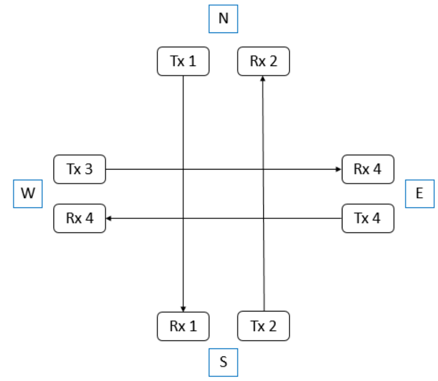

Figure 1: Design of ultrasonic anemometer with four modified HC-SR04

In [7], four sensors have been placed in front of each other to calculate horizontal and vertical component of wind. Transmitter of modified HC-SR04 sensor is kept in perfect line-of-sight with its receiver as shown in Fig. 1, 2, and 4 where Tx-1 and Rx-1 represents transmitter and receiver of sensor 1 respectively, same notation has been followed for other sensors as well. As speed of sound depends on many factors such as temperature and humidity which could reduce the accuracy of ultrasonic anemometer but this dependency has been removed in [7] by using (1) and (2). Following that conversion of components from rectangular to polar coordinate i.e., by using (3) and (4) wind speed and its direction has been obtained. If wind blows from East to West, please refer to Fig. 1, then duration $t_3 > t_4$. Hence, vertical component will have some negative value, however, t_1 and t_2 will remain same due to which horizontal component approaches to zero. Thus, 270° represents that wind is blowing in East. Further in-depth analysis has been presented in Table 1 of [7].

2.1. Problem Statement

Initial version, in [7], of ultrasonic anemometer had following problems. 1) It cannot withstand harsh weather condition and rain can easily damage its electronic circuitry due to simpler and wooden type of casing. 2) Adapter cable is required to provide power through direct source which makes it difficult to deploy at remote sites. 3) ESP module requires Wi-Fi router and internet service provider (ISP) to upload data on cloud. Thus, causing an overhead of arranging router and keeping ultrasonic anemometer within range of router signals. In addition to it, no such internet facility is available at remote locations. 4) The software and hardware is not optimized in terms of power efficiency. Thus, in this research the authors have tried to overcome the mentioned problems by proposing additional features into existing ultrasonic anemometer given in [7].

2.2. Components Used

Main electronic components used for complete design of IoT enabled ultrasonic anemometer are; AVR Atmel 328 microcontroller, ESP8266 module, SIM 900, LM2596 module, solar panel and cheapest sonar sensor HC-SR04. Interfacing of respective components with ATMEGA328 microcontroller has been done to collect and upload wind data on cloud. Ultrasonic sensor, microcontroller and SIM-900 functions at *5V* however for SIM-900 a higher current rating close to *1A* is required. HC-SR04 sensor has accuracy of ±29.1µs which makes it very difficult to design ultrasonic anemometer because a few µs of fluctuation in Time-of-flight (tof) would result in incorrect measurements for wind velocity, hence, calibration of ultrasonic sensors has been carried out through proper averaging rules. Fine-tuning of error has also been carried out to achieve accuracy of ±1µs.

2.3. Prospposed Solution

2.3.1. Frame design with minimum air turbulence

The casing of sensor has been enhanced by laser cutting acrylic sheets in place of wooden pillars used in [7]. This new acrylic based structure has been designed in a way to keep electronic circuitry safe in a box, please refer to Fig. 2 and 4. Thus, the enhanced casing of sensor makes it possible to survive rain and withstand harsh weather conditions while keeping transmitter and receiver in open atmosphere without causing air turbulence.

2.3.2. Improving communication

The communication through Wi-Fi module has been replaced with SIM-900 module. SIM-900 module has its own set of AT commands to configure its operation. Any mobile network operator, with internet package can be used with SIM-900 to upload data on cloud. Since cellular networks are already providing coverage at large extent and to most of the locations including urban and rural. In future, more feature rich communication is expected to be provided by cellular networks in the form of 5G. Therefore, the issues due to Wi-Fi unavailability at remote locations has been resolved through use of cellular technology.

Figure 2: Frame and circuit of advance version

2.3.3. Solar Circuitry

A separate PCB for solar charging circuit has been designed as shown in Fig. 2. It charges lithium-ion battery which provides power to whole circuitry. Charging circuit has been designed using two 3904-NPN transistors, TIP-127 Darlington bipolar power transistor and a Zener diode. Zener voltage of D1, as shown in Fig. 3, should be equal to voltage of battery to enable charging. Simple logic behind working of circuit is that, when voltage of battery is less than Zener voltage then low logic is passed to base of Q1 through anode of Zener which turns on Q1. Now Q2 gets OFF because of high logic passed by collector of Q1 to its base thus, Q2 sends low logic to base of TIP-127 transistor. TIP-127, being a PNP transistor, is capable of handling inputs from two transistors, gets ON and shorts the positive pins of solar panel and battery connected to its emitter and collector respectively. Charging is continued unless the voltage of battery gets more than Zener voltage which will pass high logic to base of Q1. Thus, making Q1 OFF, Q2 ON and TIP-127 OFF to stop charging.

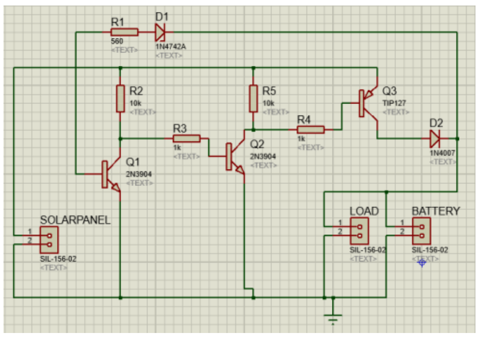

Figure 3: Charging circuit for Solar Panel and lithium-ion battery

Figure 4: Testbed deployment of advance version of ultrasonic anemometer

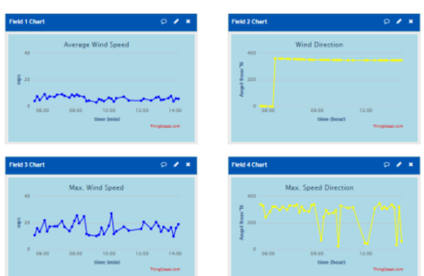

Figure 5: Real time wind data uploaded on cloud

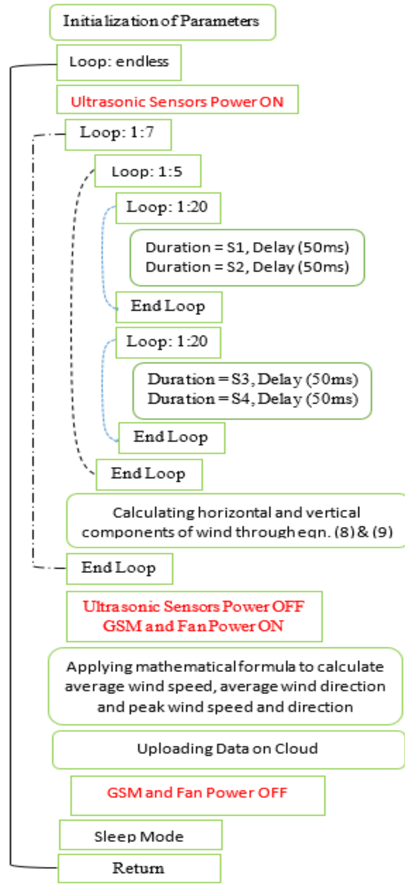

Figure 6: Software flow of advance vision of ultrasonic anemometer

2.3.4. Improving power efficiency

Power to all the ultrasonic sensors and cooling fan has been provided through transistor based switches that are controlled by microcontroller. High rating current and power to SIM-900 is provided through LM2596 module; its enable pin is connected with microcontroller to turn on/off power for SIM-900 module. Software flow shown in Fig. 6 reveals that power in all components has been utilized efficiently. Since the components interfaced with micro-controller draw power only when they are performing some operation, otherwise they are kept off. Furthermore, sleeping modes in software have been enabled which consumes least amount of power between successive readings of designed anemometer sensor.

3. Error minimization using machine learning

In [7], regression model of machine learning has been used to calibrate ultrasonic anemometer due to which certain bias was observed in data. Data from NRG-40H was used as ground truth, and we were able to minimize error to some extent on pre-processed data of ultrasonic anemometer [7].

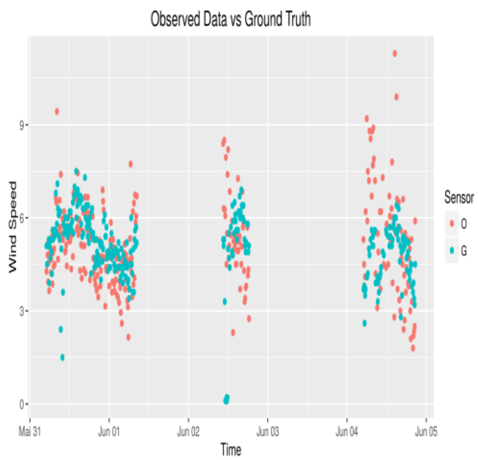

Figure 7: Observed data from ultrasonic anemometer vs ground truth data from NRG 40H

3.1. Data

ESMAP Tier2 meteorological station deployed at NED UET has NRG-40H sensor for measuring wind velocity, shown as blue dots and red dots represent data from ultrasonic anemometer in Fig. 7. Time stamp of data was 20 minutes and around thousand readings were used for training models. Before any network the data contained a mean squared error of 3.285. Fig. 7 shows that ultrasonic anemometer is capturing the general trend of wind velocity; however there is certain nonlinear bias present in the data. To account for this bias term, authors tried following models with an objective to reduce the mean squared error.

3.2. Linear Regression models

Four linear regression models were tested using R language Table. 1. However, any significant improvement in mean squared error was not achieved.

TABLE I. Linear regression models with their features and mean squared error values.

Model	Features	Mean Squared Error
1 Linear	Observed wind speed	3.0484
2 Linear	Observed wind speed, temperature	3.0864
3 Polynomial	Observed wind speed, (Observed wind speed)^2	3.3233
4 Polynomial	Observed wind speed, (Observed wind speed)^2, temperature, (temperature)^2	3.2852

4. Error minimization using deep learning

On closer observation of machine learning approaches, we found that, the error did not only depend on observed value at that particular time stamp but also on the sequence of readings observed in the past. Thus, a model capable of somehow incorporating this sequence dependence is likely to produce better results. Hence, state-of-the-art deep learning techniques called Long Short Term Memory (LSTM) was used to minimize error of ultrasonic anemometer. To account for this memory element, we replaced the regression based learning models with a (LSTM) network [8], as shown in Fig. 9. LSTM network is a recurrent neural network (RNN) which uses LSTM cells instead of simple perceptron.

4.1. LSTM cell

The key difference between LSTM and other RNN networks is its cell. An LSTM cell consists of a state and three gates as shown in Fig. 8; forget gate, input gate and output gate. These gates are sigmoid layers which decide what information to pass through the cell state by returning a value in between 0 to 1 and its product with the cell state. The forget gate decides what information to throw away from the previous state. The input gate separates out useful information from the current input and the output states, decides what to produce as the output of the network. It is because of these gates that an LSTM is able to remember information obtained in a distant past but converge quickly avoiding the vanishing gradient problem [9].

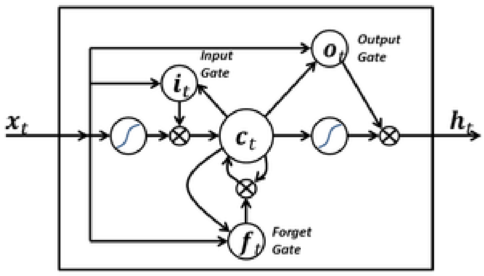

Figure 8: A typical LSTM cell

4.2. LSTM for regression

LSTM networks are most commonly used for sequence prediction problems. Due to this, they have found their way in areas like Speech Recognition [11], Optical Character Recognition [10] and etc. The output layer of an LSTM network is a softmax layer containing k labels, where k denotes number of outputs. However, for the problem under consideration in this research, outputs are not limited to a set of labels that the network can predict. To solve this problem, we used two approaches. In the first approach, we modified training set in order to train a typical LSTM model on it. Whereas, in the second one we modified the LSTM network for required results. In both approaches a network with one hidden layer having hundred nodes was used. However, different libraries for implementing LSTM were used in each approach.

4.2.1. Approach 1

The data set was rounded off to one decimal place. Since wind speed typically does not exceed 36 miles per hour (mph), the readings were divided in between 0 to 36, in the form of 360 labels. After this, with the help of simple pre-processed data from deployed ultrasonic anemometer, the LSTM was trained. This method solved the problem of error using input as a sequence of labels and predicted the output as another sequence of labels. Fig. 9; shows the model of the network for this approach. OCRopus, which is a free document analysis and optical character recognition (OCR) tool and uses bi-directional LSTM for OCR was used for implementing the model.

There are, however, several limitations in this approach. One limitation is in the number of outputs such a network can predict. Since the output layer has only 360 elements, it can only produce 360 different values as outputs. In case of a cyclone or an extremely powerful gust, this method will fail to produce any output. Also, since there are too many classes there is a high probability that many classes will not appear too much and hence will be easy to classify whereas, the ones which appear regularly may become confusing [12]. Thus, instead of modifying our training parameters, we made a slight change in the LSTM network which is discussed under. Different input sequences were used to train the LSTM network Fig. 11; and their root mean square values were compared Table. 2. Even with all the limitations mentioned, this network produced great results on input data of sequence length 8, please refer to Table. 2.

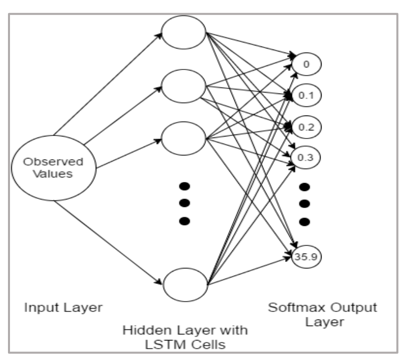

Figure 9: LSTM Network used in approach 1.

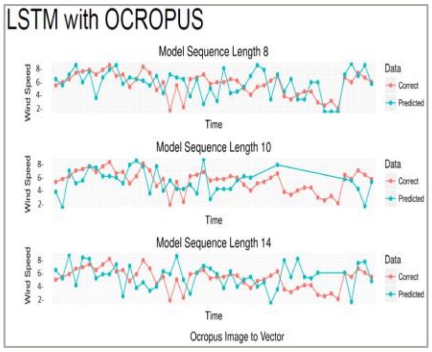

Figure 10: Visualization of results using approach 1 performed with ggplot2 R

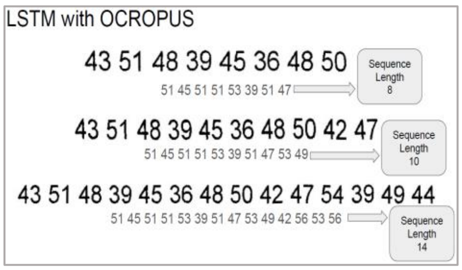

Figure 11: Different input sequences used in approach 1

TABLE II. Results of approach 1.

Model	Mean Squared Error
Sequence length 8	1.776
Sequence length 10	5.597
Sequence length 14	2.763

The network Fig. 9; will take a sequence of labels as input and give a vector of 360 values as output with probability for next label in a sequence. The label with highest probability will be finally chosen as output. Fig. 10; shows that model is fitting curve more properly for model sequence of length 8, and hence has the least mean squared error of 1.776.

4.2.2. Approach 2

In this approach, authors trained LSTM to perform regression instead of classification i.e. Neural Network as a function approximator. Instead of using a 360 unit softmax layer with sigmoid units as outputs, we used a single cell with a Rectifier Linear Unit (ReLu) activation. Advantage of ReLu function is that, unlike a sigmoid unit it can be used to model positive real numbers. It also helps speeding up the process in backpropagation and reduced the computation time of a single classification as well [13]. Rectifier activation function is defined as:

$$f(x) = \max(0, x) \quad (5)$$

Using this approach, we were able to reduce the mean squared error to 0.572 on the test set, please see results given in Fig. 12. Keras python library was used to implement LSTM network with theano backend.

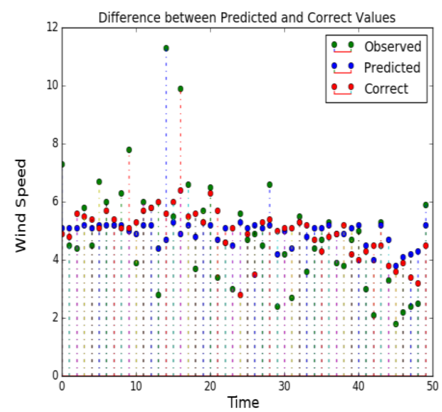

Figure 12: Visualization of results from Approach 2 matplotlib python

5. Conclusion

Observing the significance of weather data in scientific research, artificial Intelligence (AI) and other related fields a cost effective and commercially deployable ultrasonic anemometer has been designed, and calibrated in this research. Real time readings have also been obtained through cloud to make it a complete IoT enabled device. The testbed of anemometer was deployed at roof of CIS dept. NED UET and rich amount of data has been collected. Its calibration has also been carried out using LSTM, a deep learning technique. Addition of solar panel, battery, and GSM provides smooth operation and connectivity at remote locations. Through GSM, loss rate of data during uploading on cloud has also been reduced. Future directions include; 1) to enable two-way communication through GSM to perform actuation in real time when required. 2) Integrating rain, dust, altitude, pressure, temperature and humidity sensors along with designed ultrasonic anemometer to make a complete weather station device. 3) Exploiting more powerful machine learning techniques for making weather prediction. 4) Integrating Bluetooth module and observing data on android app without any internet connection.

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