Ultra-Low Cost Vehicle Data Acquisition and Transfer System from Analog and Digital Sensors to Audio Channel of a Phone

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***Abstract*— The proposed system acquires and transfers data from a vehicle's analog and digital sensors to the user's very own mobile phone. The device uses a microcontroller to accept the sensor inputs and generate an audio signal indicative of the data acquired by the sensors and an audio jack which on inserting into the phone acts as a channel to transfer the data collected by the sensors to the cell phone. This data acquired from the sensors is fed to the microphone jack of the cell phone which is then processed by a mobile application and decoded sensor values are displayed on the cell phone. The ultra-low cost nature of the technology enables new additional applications like: On-The-Spot Soil Testing, Home Automation, Traffic Data Capture and Health Data Capture, etc. at disruptive prices.**

***Keywords*— Data Acquisition, Digital Signal processing, Fast Fourier Transform, Spatio-Frequency Encoding, Time Division Multiplexing, 3.5 mm Audio jack**

I. INTRODUCTION

Vehicle data acquisition is a crucial part of automotive sensing techniques. In order to achieve this, various approaches have been proposed. Technologies like USB [1], Bluetooth [2], Wi-Fi [3] and NFC [4] have been extensively used to facilitate intra-vehicular communication. However, these technologies are differently implemented in different phones which hamper their compatibility to a great extent. Additionally, these technologies also require substantial hardware which increases the cost, complexity and power consumption of the entire system. To enable vehicular data acquisition systems in 2-wheelers and low end commercial vehicles like 3-wheelers in emerging countries, we propose a technology to achieve the same at disruptive costs. Our system uses analog signals in the audible frequency range to establish communication between various devices and the user's very own mobile phone. Every mobile phone recognizes the audible range of sound signals which makes it a cogent choice for our application. This technology finds its applications in various domains –

- Automobiles – Connected Car [5], [6] Technology
- Medical – Health Data Capture and Transfer
- Agriculture - On The Spot Soil Testing
- Domestic – Home Automation
- Infrastructure – Traffic Data Capture

However, in this paper we focus on vehicular communication systems. Considering the example of Connected Cars, one can observe that installing a cellular GPS system on a vehicle is both complex and cost intensive. On the other hand if we read the data in a mobile phone, we can use the pre-existing GPS/ GPRS technologies present in it, thereby reducing costs drastically. The SIM card of the mobile phone can also be used to communicate with servers and satellites. On the cost side, it is important to note that the cost of the device (GPS, SIM, Battery etc.) gets entirely shifted to the user's own cell phone having all the aforementioned features thus eliminating the need for additional circuitry making our system more resourceful and an economically apt choice.

We leverage the fact that worldwide mobile phone penetration is increasing by the day. Thus reusing the resources present in the existing smartphones and their platforms (Android, 3G etc.) reduces the complexity of data processing and transmission.

II. PRIOR ART

Prevailing systems use wireless and near field communication to acquire vehicle data and transmit it to a mobile phone. Transceivers are provided which are configured to communicate wirelessly within the vehicle with a cell phone using Bluetooth communication protocol as adopted in the said system [7]. Radio frequency transmission technology has been put into use in existing systems [8], [9] which transmit internal (subsystems, ambient temperature etc.) or external (roadway, atmosphere, etc.) vehicle data to a vehicle operator or an external site.

The system cited in [10] uses a vehicle portable device to acquire the vehicle information which is transmitted from the vehicle by wireless communication. It makes use of a transmission controller that controls the transmission of the vehicle information to the mobile terminal by near-field wireless communication. While the above mentioned systems use sensors to acquire vehicle information, yet another system

[11] uses a camera which when pointed to a vehicle transmits information through images to a mobile computing device which is preferably a mobile phone having at least a camera, a display, a processor, and a tangible non-transient computer-readable medium for storing appropriate programming and vehicle information.

Square Reader [12] is a small plastic device that comprises of a read head for passing a magnetic stripe of a card to read the stored data and produce an analog signal indicative of it which is provided to a cell phone through an output jack. The signal containing the magnetic strip data is transmitted to the phone microprocessor which amplifies, samples and decodes the data with the aid of a pre-installed application. However, in our system the acquired sensor data is Spatio-Frequency encoded leveraging properties of sound waves and transmitted in the form of audio signals to the cell phone.

III. Spatio-Frequency Encoding

We have used Spatio-Frequency encoding to transfer the sensor values to the phone. In this, the sensor output is Spatio-Frequency encoded leveraging properties of audio signals.

The output of the sensor is converted to an audio signal as shown in (1).

$$Y(t) = C\sin(2\pi f_t t) \tag{1}$$

In this conversion, the signal from the sensor undergoes spatial encoding as the sensor output is converted into a continuous audio signal with frequency indicative of the output of the sensor as shown in Figure 1(a). Eq. (2) shows the Fourier Transform (FT) [13] of audio signal in (1).

$$Y(X) = FT\,(Y(t)) \tag{2}$$

The signal $Y(X)$ is now frequency encoded in which the ideal frequency response ($H(X)$) of the phone microphone is normalized using an inverse frequency response ($H'(X)$) to achieve a constant flat filter response (for maintaining constant SNR) in the desired frequency range as shown in Figure 1(b). Thus the sensor output is first encoded in the spatial domain and then in the frequency domain to obtain optimum results for our system.

The resultant Spatio-Frequency encoded signal ($Y'(t)$) is given by

$$Y'(t) = IFT(\,Y(X) * H'(X)\,), \tag{3}$$

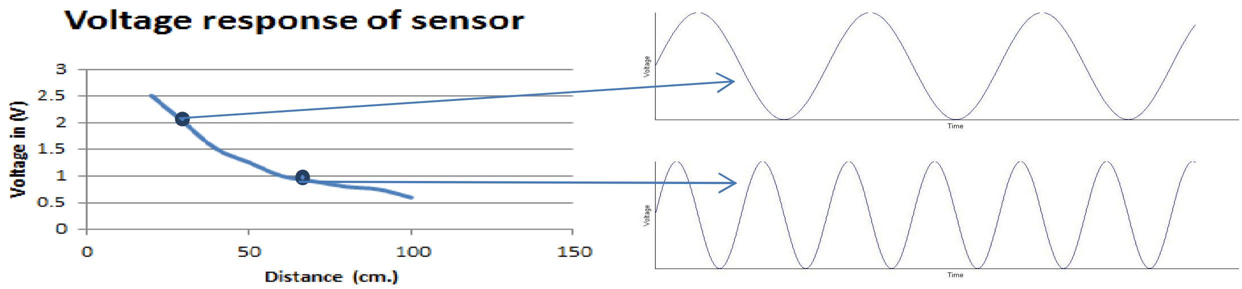
where IFT denotes Inverse Fourier Transform.

IV. Proposed Approach

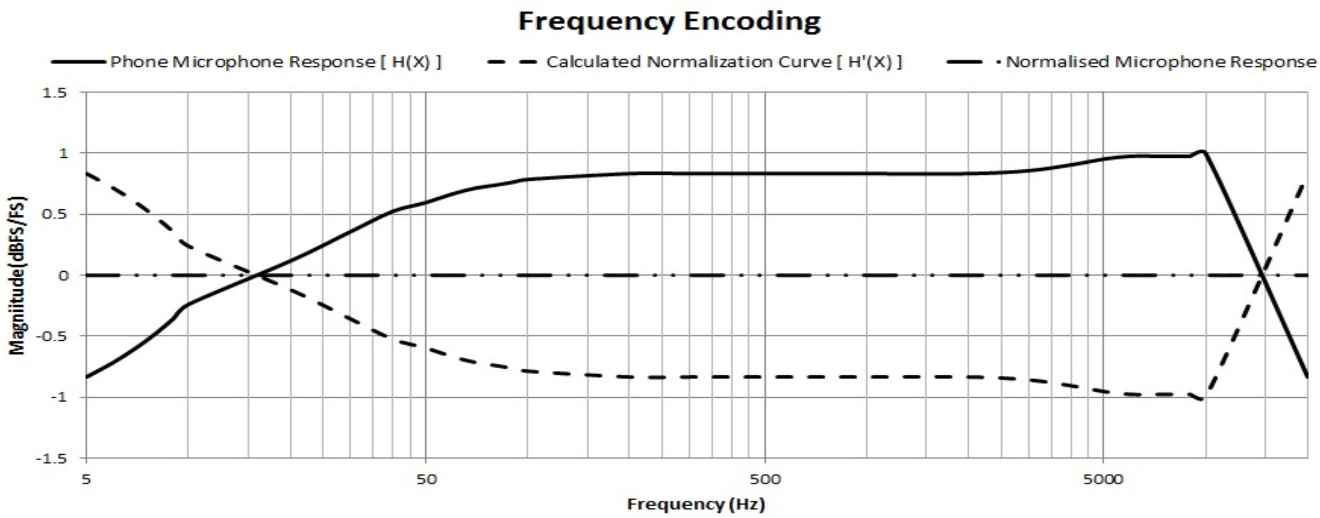
A. Algorithmic Methodology

As shown in Table I. consider the output of the sensor to be

Spatial Encoding



(a) Spatial Encoding: The sensor values are converted to audio signals having different frequencies



(b) Frequency Encoding: This shows the normalization of the phone microphone frequency response

Figure 1. Spatio- Frequency Encoding

$$S(t) = g(D). \quad (4)$$

This signal is given to the ADC of the microcontroller which converts it into 12 bit digital samples. Therefore the digital value S_{ADC} can be represented as

$$S_{ADC} = \left(\frac{S(t)}{V_{ref}}\right) * 2^{12}, \quad (5)$$

where V_{ref}= Reference voltage of the ADC.

Depending on this value acquired from the sensor, a sine wave with proportional frequency in the audible range of sound is generated from the microcontroller as seen in (1). This signal after Spatio-Frequency encoding is routed through the audio cable to the mobile phone via the 3.5mm audio jack like any other sound wave. The signal received by the phone microprocessor is then sampled [14] at a frequency of 44100 Hz. The sampled signal can be represented as

$$Y(n) = C\sin\left(2\pi\left(\frac{f_t}{f_s}\right)n\right). \quad (6)$$

These digital samples are used to calculate the frequency of the signal using the Cooley-Tukey FFT [15] algorithm. Once the frequency is computed, linear regression is used to map it to the value of the distance of the object from the sensor which is then displayed on the screen.

For interfacing multiple sensors simultaneously we have used the concept of Time Division Multiplexing in which the signal corresponding to each sensor is sent to the phone for a predefined time interval. Consider N sensors S_1, S_2, S_3, up to S_N having outputs $S_1(t)$, $S_2(t)$ up to $S_N(t)$ respectively. Each of the sensor output is sent to different ADC channels of the microcontroller. These values are then converted to corresponding digital values by the ADC. These digital values are used to generate sine waves with frequency proportional to the amplitude of the sensor outputs. In order to distinguish different sensors, a predefined frequency is attached at the beginning of each sine wave analogous to the start bit in digital data transmission. Thus a continuous train of audio signals is sent to the microprocessor of the phone with different sensor data interleaved between them. The frequency of the received audio signal is computed in the phone and the corresponding sensor data is calculated using regression equations and displayed on the screen.

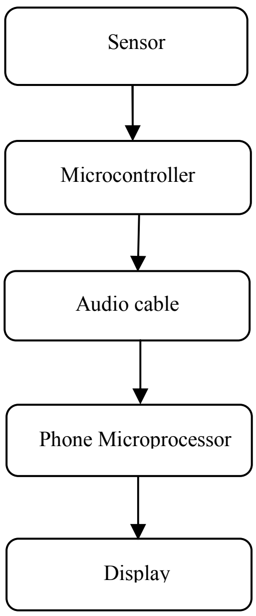
As the number of sensors N, the initial phase of the signal φ, the reference voltage for the ADC module V_{ref} and the sampling frequency in the phone f_s remain fixed, the system becomes universal and can be used with any cell phone.

B. Hardware Used

1) Microcontroller: For experimental purposes, we have used the MSP 430FG4618 [16] microcontroller manufactured by Texas Instruments. It is a 16-bit mixed signal RISC microcontroller which is capable of handling both analog and digital signals thereby increasing the scope of our experiment.

2) 3.5mm Audio Jack: The 3.5mm jack having the TRRS (Tip Ring Ring Sleeve) topography has 4 contacts: Tip (Left speaker), Ring (Right speaker), Ring (Microphone), Sleeve (Ground) separated by insulators. The audio jack is capable of accepting analog audio signals through the microphone which can then be processed by the phone.

TABLE I. SYSTEM OVERVIEW



Signal Representation	Parameters
$S(t) = g(D)$	t = Time $S(t)$ = Voltage output of the sensor $g(D)$ = Function varying with respect to distance D
$f_t = h(S(t))$	f_t = Frequency generated by the microcontroller corresponding to distance of the object at time t $h(S(t))$ =Function varying with voltage output of the sensor
Spatial Encoding $Y(t) = C\sin(2\pi f_t t)$	$Y(t)$ = Audio signal generated by microcontroller C = Maximum amplitude of audio signal generated
Frequency Encoding $Y(X) = FT(Y(t))$ $Y'(X) = Y(X) * H'(X)$	$Y(X)$ = Frequency domain representation of $Y(t)$ $Y'(X)$ = Signal after normalization for maintaining constant SNR $H'(X)$ = Calculated normalization response
$Y'(t) = IFT(Y'(X))$	$Y'(t)$ = Spatio-Frequency Encoded audio signal
$Y(n) = C\sin\left(2\pi\left(\frac{f_t}{f_s}\right)n\right)$	$Y(n)$ = Sampled value of audio signal f_s = Sampling frequency of the phone n = Sample number
$Y(U) = FFT(Y(n))$ $dist = m(f_{comp})$	$Y(U)$ = Fast Fourier Transform of $Y(n)$ $dist$ = Distance computed and displayed on the phone f_{comp} = Frequency computed by implementing Cooley Tukey DIT FFT algorithm in the phone. $m(f_{comp})$= Function that maps computed frequency to the actual distance of the object.

3) Low Pass Filter: A simple 1st order R-C low pass filter with cut off frequency 6 KHz has been used to smoothen the frequency modulated waves outputted by the DAC of the microcontroller.
Resistor Value Used – 5.6 kΩ
Capacitor Value Used – 4.7 nF

4) Infrared (IR) Sensor: During the developmental phase, we used an analog infrared distance sensor SHARP GP2Y0A02YK [17]. An object within 1m range can be accurately detected by the sensor. The output voltage ranges from 0.5 V to 2.5 V depending on the distance of the object from the sensor.

5) Low Cost Android Phone: A low cost Android [18] phone has been used to process and display the incoming information. The device is loaded with Ice Cream Sandwich OS and can accept input signals ranging from -1.5 V to +1.5 V. The input signals fed from the audio jack are sampled at 44.1 Khz. The overall system overview is summarized in Figure 2.

C. Software

The microcontroller is programmed to continuously generate a sine wave using its DAC Module. In order to generate a sine wave, we have used a simple look-up table approach. In this, the DAC module register is continuously updated with values that represent a sampled sine wave in the overflow interrupt service routine of a 16-bit Timer (Timer B) operated in the UP mode. In this mode, the timer counts up to a specified count and when the count is reached an interrupt is generated. Thus by varying the count of the Timer overflow, the frequency of the sine wave can be varied. The working of the microcontroller is summarised in Figure 3. On powering ON, the microcontroller accepts the sensor value and converts it into digital data using the ADC module. The Timer compare register is then loaded with a count indicative of the ADC value so as to vary the frequency of the sine wave according to the value of the sensor.

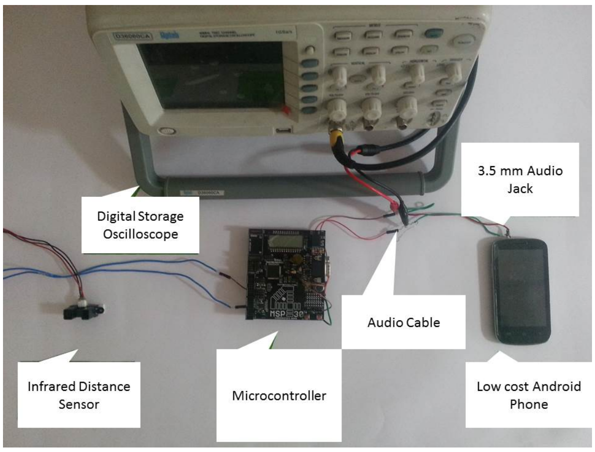


Figure 2. Overall System Overview

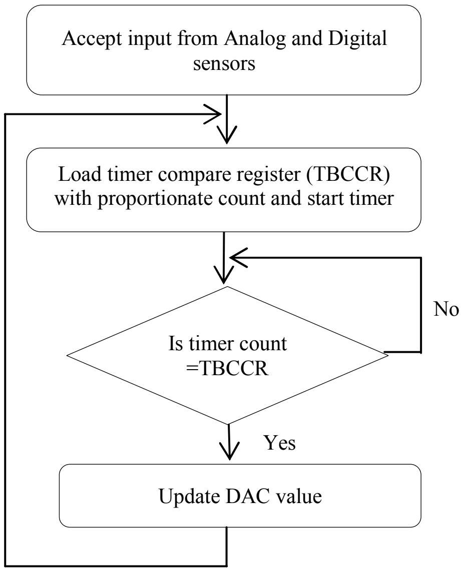


Figure 3. Algorithm for generation of audio signals corresponding to sensor output using microcontroller

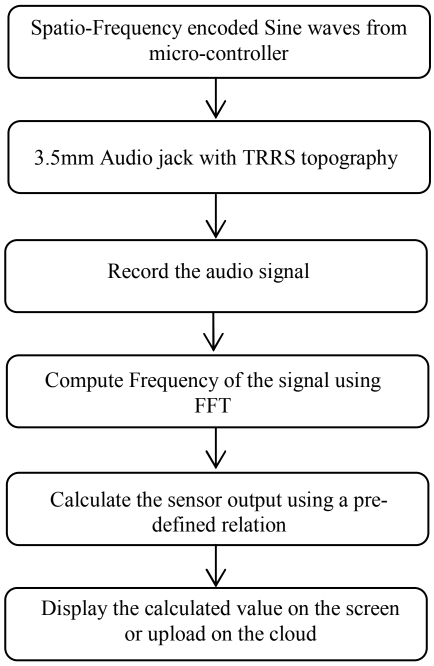


Figure 4. Algorithm for decoding frequency of the signal in cell phone

Figure 4 summarizes the processing of the audio signal in the mobile phone. The Android application reads the data from the audio buffer of the phone. This data is nothing but the sampled values of the incoming signal at the audio jack. Most commonly used sampling rate in mobile phones is 44100 Hz and the maximum buffer size that can be read at once is 4096 bytes and hence the same values have been used. The audio buffer containing the sampled values is read continuously in a separate thread. The Cooley-Tukey FFT algorithm is used to compute the frequencies from these sampled values.

V. Experimentation

A. Experimental Setup

For experimental and illustrative purposes, we have modeled the rear obstacle distance measuring systems in cars using an infrared distance sensor. Our system takes the distance data captured in voltage by the infrared sensor and transmits it to the cell phone through the audio channel. This transmission is Spatio-Frequency encoded. The phone decodes back the Spatio-Frequency encoded data into intelligible information and displays it to the user.

Figure 5 shows the experimental setup of the system during research. Both the microcontroller board and the sensor are powered using a 9V battery. We have used a DC voltage regulator IC 7805 to step down 9V to 5V. The infrared sensor output is given to the ADC0 pin of the microcontroller. The DAC0 pin output from the microcontroller is given to a low pass filter, the output of which is given to the audio jack of the cell phone.

B. Calibration

1) Distance to Voltage: Initially we calibrated the voltage level outputted by the sensor to the distance of the object from the sensor. The output of the sensor varies with the distance of the object with a voltage of 0.5 V for a distance of 100 cm and 2.5 V for a distance of 20 cm.

2) Volatge to Frequency: The acquired ADC value is mapped to the frequency generated by the microcontroller in this stage using the equation

$$TBCRR0 = 100 + \frac{S_{ADC}}{20}, \quad (7)$$

where TBCRR0 is the compare match count.
We observed that the variation in the frequency was approximately linear with 2.654 KHz corresponding to 2.5V and 5.205 KHz corresponding to 0.5V.

3) Frequency to Distance: Quadratic regression was used to accurately map the computed frequency f to the corresponding distance d as data points fit the second order curve with comparatively minute error. We have used the following two regression equations:

$$d = 4.2406f^2 - 5.4861f + 4.5536 \qquad f \leq 5KHz \quad (8)$$

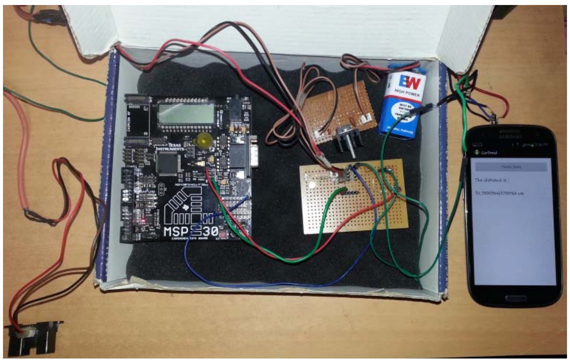


Figure 5. Experimental Setup
Above setup presents a system modeling the rear parking assist in cars using an IR distance sensor

$$d = 21.901f^2 - 120.42f + 134.550 \qquad f > 5KHz \quad (9)$$

C. Phone Application:

Figure 6 shows a screenshot of a prototype application developed for an android cell phone. Two infrared distance sensors were interfaced with the system and using time division multiplexing technique, information was transmitted to the cell phone and the corresponding distances were computed.

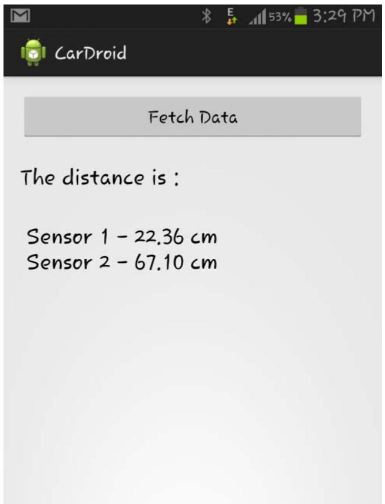


Figure 6. Android Application Screenshot
Above screenshot displays the distance of two objects from corresponding sensors interfaced using Time Division Multiplexing

D. Observations:

TABLE II. Experimental Observations

Distance of the Object (cm.)	Frequency Generated by the Controller (Hz)	Frequency Calculated in the Phone (Hz)	Calculated Distance in the phone (cm.)	Error Percentage (%)
20	2654	2680.87	20.32	1.60
25	2963	3003.46	26.33	5.32
30	3247	3305.34	32.75	9.16
35	3412	3445.31	35.98	2.80
40	3623	3639.10	40.74	1.85
45	3794	3822.14	45.53	1.17
50	3991	4015.94	50.91	1.82
55	4196	4242.04	57.59	4.71
60	4303	4328.17	60.24	0.40
65	4505	4532.73	66.81	2.78
70	4668	4694.23	72.24	3.20
75	4783	4812.67	76.37	1.83
80	4993	4958.99	81.63	2.04
85	5047	5049.03	84.86	0.16
90	5107	5102.87	90.34	0.38
95	5158	5156.71	95.96	1.01
100	5205	5199.7	100.54	0.54

VI. DISCUSSION OF RESULTS

Table II shows the values of different parameters measured during experimentation. Computed distance values were found to be approximately conforming to the actual distance values with an average error of 2.37%. The error can be minimized further by using highly sensitive sensors. The results show that our system can be effectively used to interface multiple sensors to the cell phone with the error being below the acceptable tolerance level.

VII. MERITS

- The crucial advantage of this technique of data transfer is the use of 3.5mm jack which makes the system completely universal and can be implemented using any mobile phone making it very versatile.
- The ultra-low cost nature of this system allows it to be also implemented in low end commercial vehicles in emerging countries.
- With the availability of data on a mobile phone, further improvisations can be made to the application by developing an application that communicates with a centralized server or cloud and optimizes data storage and processing.
- Although in our implementation, an infrared distance sensor was used, the ability to convert analog and digital output of any sensor to a Spatio-Frequency encoded wave allows the use of any sensor or transducer enabling the user to implement a variety of systems.

VIII. DEMERITS

- One of the limitations of our system is that it can only process speech signals thus limiting the overall system bandwidth.
- The accuracy and precision of the system is compromised as the number of sensors increase. This limits the maximum number of sensors that can be interfaced with the system.

IX. CONCLUSIONS

We have successfully developed an ultra-low cost system to interface any type of sensor to a cell phone. Secondly, our system is scalable to any number of consumers. Furthermore, using voltage divider and signal conditioning circuits, sensors of various ratings can be interfaced with our system thus making it universal.

To conclude, the system we designed provides an economical alternative to other data transfer methodologies within vehicles and drastically reduces system complexity and costs. Our system can be additionally extended for many other diverse applications like Home Automation, Medical Diagnosis, Soil Testing, etc.

ACKNOWLEDGMENT

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