A Sensor Parameter Calibration Method of Tire Pressure Monitor System Based on Linear Regression Technology

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Abstract. The regular sensors that are used for TPMS (Tire Pressure Monitor System) are some inaccuracies for collecting parameters. Thus, a new error correction method is proposed to calibrate tire pressure values based on linear regression technology. And based on the way a friendly interactive TPMS is achieved. The parameters of tire pressure sensors are determined by the experiment. And sensor parameter calibration is based on least square method to fit the values. Furthermore, a linear calibration model is obtained through continuous linear regression analysis. Finally, the optimal calibration model corrects the raw data, so the use of the model greatly improves the accuracy of TPMS. And it greatly improves the stability and flexibility of traditional TPMS. The testing and practice has proved the feasibility of the model.

Introduction

Over the past two decades, along with the economic growth has brought huge demand for logistics and other areas, the freight vehicle ownership is growing. According to statistics, nearly half of the freight vehicle accident is due to tire faulty. Especially, the abnormal tire pressure often leads to a major accident [1]. In addition, improper tire inflation pressure will dramatically increase energy consumption of a vehicle. TPMS (Tire Pressure Monitor System) can ensure that the working status of the tire is maintained within the standard range. It monitors tire pressure, temperature and other data [2]. And this prevents the accidents waiting to happen and reduces energy consumption.

Once a tire faulty is detected, TPMS will prompt or warn users through pre-matching and simple control equipment [3]. Such simple control equipment presents two issues: first, the traditional TPMS pressure sensor is inaccurate. Their built-in correction factor is too simple for the high-pressure tires on heavy freight vehicles. Second, the absence of user interaction function on a traditional TPMS reduces the flexibility of the system. Moreover, it limits the further applications of the system [4]. Considering the drawbacks of traditional TPMS, a freight vehicle oriented high-precision interactive TPMS is proposed. And the new TPMS utilizes mobile cellular network to transmit data to the data center for further analysis. We introduced a linear regression model to the sensors of TPMS for parameter calibration. After that, a smartphone is utilized to achieve better user interaction. Due to strong processing performance, the smartphone is equipped with an application that implements more advanced calibration algorithm.

Technical Framework

A. System Application Overview

In our solution, the TPMS monitors real-time tire pressure and other data to ensure the vehicle can travel at a standard tire pressure and temperature. The sensor components are mounted on each tire valve stems externally to measure the tire pressure and tire temperature. A sensor wirelessly transmits raw data to a communication terminal [3]. Sometimes, a relay transmitter is necessary for extending the communication range on a long truck. After receiving the raw data from any sensors, the communication terminal wirelessly transmits formatted data to an Android-based smartphone. Any abnormal tire pressure, once it's detected, sets off the alarm both on the smartphone and the communication terminal. The application will request a roadside assistance under the permission of users. The rescue center receives a rescue request and verifies the information such as tire type. The utilization of the smartphone significantly extends the interaction feature of the TPMS. During the whole assistance procedures, users, rescue center and rescue vehicle share necessary data such as faulty vehicle position, tire status or remaining assistance time. And the system structure diagram is shown in Fig.1:

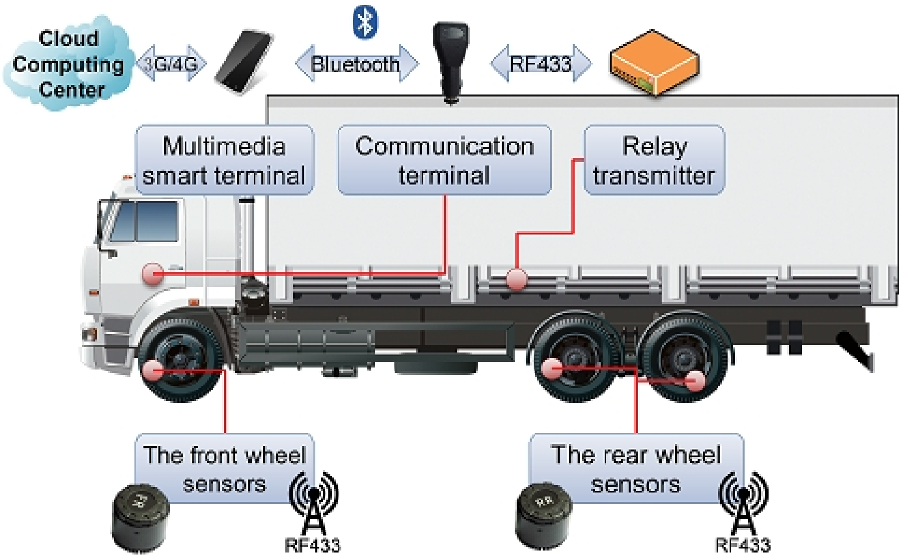

Fig.1. System structure diagram

B. Hardware and Software Framework

The system hardware mainly consists of three hardware components: the tire pressure sensor, the communication terminal and the relay transmitter. Fig.2 presents two tire pressure sensors and one communication terminal. The bigger object is the communication terminal. The sensor amount depends on wheel amount of the vehicle.

Fig.2. Two tire pressure sensors and one communication terminal

The component of tire pressure sensor is based on SP370 from Infineon. We optimized the power management to extend battery life. The metal shell and the antenna are combined together. Such a design adapts to operating condition of the system. The communication terminal acquires power through the car cigarette lighter. All the hardware components are connected wirelessly. There are two communication stages. In the first stage, the connection between sensors and communication terminal is one-way from a sensor to terminal through RF 433MHz. In this stage, a relay transmitter may be necessary for extending the communication range. In the second stage, the communication terminal is connected with a smartphone through Bluetooth. The communication terminal transmits encrypted data to the smartphone. The encryption is introduced for integrity checking, not for security reason.

The main function of software is to monitor and display the current tire pressure and tire temperature in real-time. In this paper, the application realized calibration algorithm, and the calibrated data are accurately displayed. Application continuously monitors the continuous state change of tires, and then early warns for tire abnormal condition. In addition, the application provides users with roadside assistance and other auxiliary services. Application receives tire pressure data in the form of Bluetooth communication, and conducts sensor parameter calibration. According to the respective sensor which is mounted on each tire, users match on each tire pressure sensor ID. Then the data of each tire is sent to the intelligent terminal interface in the form of broadcast. The system stores the matched sensors, and intelligent terminal will be real-time monitoring the tire pressure, temperature and other data of each tire.

C. Sensor Calibration

Sensor calibration is a process to build a mathematical model based on the measurement principle, and an output value is obtained corresponding to the different input value. Finally it can get a sensor calibration model. In order to make the collected tire pressure values and the actual tire pressure values close as much as possible, regression analysis should be carried out continuously. Regression analysis can be considered as a process of circulation, which is based on sample data, and use some statistical methods to solve the relationship between variables [5]. This process is sometimes necessary to be repeated several times until the model can get to meet the assumption and properly fit the data. So tire pressure calibration is far easier to achieve by using hardware.

In actual measurement of tire pressure, there are random errors in tire pressure values that are measured by the tire pressure sensors. This paper assumes that the error exists in a linear way, and it obtains a linear regression model by continuously collecting a large number of tire pressure data and conducting regression analysis.

Sensor Calibration

A. Data Collection

In this paper, all the data is collected from static tires. For convenience reason, the tire is inflated to the maximum pressure. Then the tire is deflated and the changing pressure values are recorded by multiple gauges and the tire pressure sensor to be calibrated at the same time. Tire pressure data acquisition step follows:

First, multiple tire pressure gauges are utilized to record the actual tire pressure. The average measurement is considered as a standard measurement, or ground truth. Both analog and digital display type of tire pressure gauge is utilized to avoid individual error.

Second, during the same deflating procedure, the measurements from the calibrating sensors are recorded. The recording operation is implemented on the smartphone application.

According to the above steps, multiple sets of tire pressure data are collected. These data provide a powerful support for the following regression analysis. Due to the limited space of the paper, we cannot list the entire data. 15 sets of tire pressure data is shown in Table 1.

B. Data Analysis

Tire pressure data that is obtained by the tire pressure sensors on the tire external presents random errors, so it is required to obtain the sensor calibration model to calibrate the data. A simple analysis of data can be drawn, the true value is larger than the sensor value about 100kpa, and this means that the value that is acquired by the sensor is the current value of absolute pressure, while the analog or digital measures the relative pressure of the tire at atmospheric pressure. Even if the tire pressure sensor is exposed in an open environment, it can measure the pressure about 98 ~ 101kpa. In order to effectively calibrate sensor values, the least square method is used for linear fitting in this paper.

Table.1. The tire pressure data collection table

No.	Analog values (kpa)	Digital values (kpa)	Standard values (kpa)	Sensor values (kpa)
1	300	300	300	397
2	295	295	295	391
3	293	290	291.5	388
4	290	290	290	386
5	280	280	280	386
6	270	270	270	372
7	263	265	264	370
8	260	260	260	365
9	250	250	250	360
10	244	245	245	351
11	240	240	240	336
12	235	235	235	332
13	230	230	230	330
14	227	225	226	325
15	225	225	225	322

Ideally, the sample data should be collected as much as possible over a wide range to improve accuracy. However, under realistic conditions, we can only collect data within a limited range. In this paper, the sensor values are defined as the variable x, the standard values are defined as variables y. They may satisfy prototype function $y = ax + b$, so it is required to get the value of least-square solutions to satisfy the above data [6]. First, drawn from the scatterplot in Fig.3, the black dots represent discrete points. Second, from the graphical point of view, substantially discrete points fall on a straight line, so it is a linear relationship between the measured value and the true value of the tire pressure, and it can be determined by a linear fit to satisfy the relationship between the discrete points. It is assumed that a linear model, $y = ax + b$, is found out, then the following least square method is used to calculate the value of a and b [7,8].

For sample data $x_i \left(i \in N^*\right)$, supposing

$$D = \sum_{i=1}^{n} \left[y_i - \left(ax_i + b \right) \right]^2 \tag{1}$$

When the minimum value of D is found, as in Eq.1, fitting level is the best state between the fitting line and the observation of point. Least squares principle is determined to obtain the value of a and b that can get the minimum value of D, if the D is seen as a function of a and b [9], according to the condition of the multivariate function that takes the value, the above problems are solved by solving Eq.2, as follows:

$$\begin{cases} \dfrac{\partial D}{\partial a} = -2\sum_{i=1}^{n} \left[y_i - (ax_i + b) \right] x_i = 0 \\ \dfrac{\partial D}{\partial b} = -2\sum_{i=1}^{n} \left[y_i - (ax_i + b) \right] = 0 \end{cases} \tag{2}$$

By solving Eq.2, the value of a and b can be obtained. Making $nx = \sum_{i=1}^{n} x_i$, $ny = \sum_{i=1}^{n} y_i$, then we can calculate Eq.3 ,even if:

$$\begin{cases} n\overline{y} - na - bn\overline{x} = 0 \\ n\overline{xy} - an\overline{x} - bnx^2 = 0 \end{cases} \tag{3}$$

Then simply for ease of accounting, Eq.3 is switched to matrix form, and eliminates n, then we can work out a and b, as in Eq.4.

$$\begin{cases} a = \overline{y} - b\overline{x} \\ b = \dfrac{\overline{xy} - xy}{\overline{x^2} - (x)^2} \end{cases} \tag{4}$$

As a result, the related parameters in the linear regression equation can be obtained according to the result of curve fitting. If the fitting results are not satisfied, steps fitting may repeat many times. It can be learned, a linear calibration model of tire pressure values is that, *f(x) = 0.9675x-89.0485*. Fitting curve is shown in Fig.3 as solid blue line, wherein the horizontal axis is the tire pressure value of sensor, the vertical axis represents the actual value of the standard tire pressure.

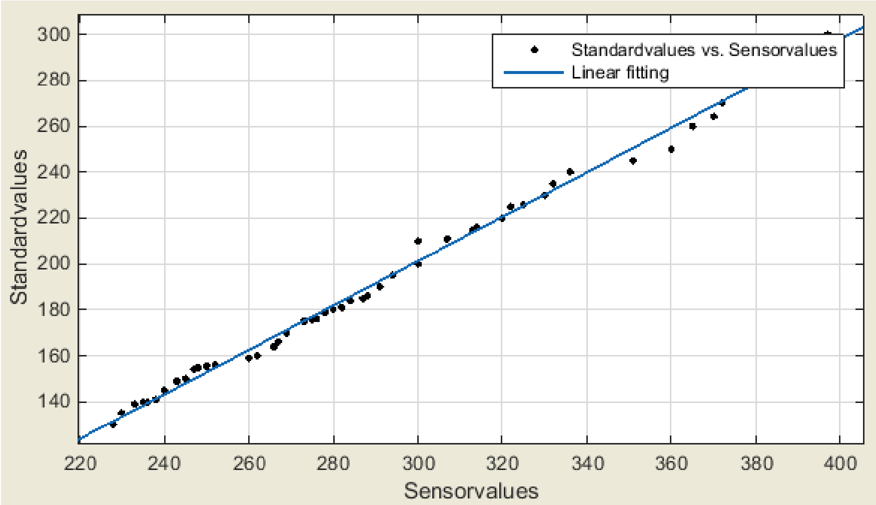

Fig.3. Linear fitting

C. Model Validation

In order to verify the validity and accuracy of the model, several groups of data were selected for holdout validation. We list 20 groups of data. After putting each group data into a linear regression model to be calculated, the calibration values and deviations of tire pressure can be obtained. Then Table 2 shows the comparison of the measured tire pressure data with the calibrated data.

Table.2. Bias and bias ratio after calibration data

No.	Sensor values (kpa)	Standard values (kpa)	calibration values (kpa)	Bias	Bias ratio
1	275	175.5	177.0139	-1.5139	-0.855%
2	273	175	175.0789	-0.0789	-0.045%
3	269	170	171.2089	-1.2089	-0.7%
4	267	166	169.2739	-3.2739	-1.934%
5	266	164	168.3064	-4.3064	-2.56%
6	262	160	164.4364	-4.4364	-2.7%
7	260	159	162.5014	-3.5014	-2.15%
8	252	156	154.7614	1.2386	0.8%
9	250	155.5	152.8264	2.6736	1.75%
10	248	155	150.8914	4.1086	2.7%
11	247	154	149.9239	4.0761	2.7%
12	245	150	147.9889	2.0111	1.356%
13	243	149	146.0539	2.9461	2.0%
14	240	145	143.1514	1.8456	1.3%
15	238	141	141.2164	-0.2164	-0.153
16	236	140	139.2814	0.7186	0.5%
17	235	140	138.3139	1.6861	1.219%
18	233	139	136.3789	2.6211	1.92%
19	230	135	133.4764	1.5236	1.14%
20	228	130	131.5414	-1.5414	-1.17%

By calculating and comparing, tire pressure values that are calibrated and the actual values that are measured by the tire gauge have deviations within 10kpa, and the ratio of the deviation is within 3.6%, indicating that the result of fitting is better, and the degree of fitting is higher, and linear correlation is strong.

Through experimental verification, TPMS uses the above model to calibrate sensor values, and gets accurate values in real time by using pre-matching and self-developed tire pressure sensors. And the calibrated tire pressure is higher accuracy, and TPMS can be re-match and get the sensor values, and finally the calibration model has practical value.

Conclusions

Based on least square linear regression technology, a linear calibration model is established to calibrate the parameter of tire pressure sensor through fitting the data and continuous data analysis. As a result, TPMS obtains the precise tire pressure by external sensors which are mounted on the wheel in real time. First, the measured tire pressure is calibrated to be the standard tire pressure parameters by using the sensor parameter calibration model, and it provides an effective and reliable basis for collecting tire pressure data. And the tire pressure data that is calibrated by the calibration model have reliability and validity. Second, the sensor parameter calibration model greatly improves the measurement accuracy and interactivity of TPMS through applying the optimization algorithm. But the accuracy of the tire pressure data are slightly less than, so a further research is the need for more accurate calibration of the model parameters, and it lays the foundation for future real-time monitoring tire pressure.

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