Wireless vehicle detection node based on tunnelling magneto resistance sensor

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Received 15 September 2014, www.cmnt.lv

Abstract

A wireless node based on tunnelling magneto resistance sensor was designed for large scale vehicle detection in Intelligent Transport System. With regard to the sensor's characteristic of high resistance, rapid response and high linearity, the signal acquisition and regulation circuits were designed to meet the requirement of geomagnetic measure for three dimension axis of the sensor. A vehicle noise pre-detection unit was implemented to wake up the microcontroller from sleep state before vehicle enter the detection area. Low power chips were considered and the all sensor units were power supplied by MCU, cooperated with the improved power-efficient ATA algorithm, the power consumption was minimized. Experimental results showed that the designed node was capable of capturing the magnetic feature of different vehicle types and on line vehicle flow detecting for long time.

Keywords: tunnelling magneto resistance, geomagnetic induce, vehicle detection, ATA, WSN

1 Introduction

Vehicle detection and recognition is one of key technologies in Intelligent Transport System (ITS). From vehicle detection sensors, road traffic information are gathered, such as the vehicle occupying, driving in and departing, the vehicle speed and traffic flow. Currently, Surveillance technologies can be divided into two types, the Intrusive and Non-Intrusive [1]. Sensor used in the former are often embed under the surface of the pavement. Examples include inductive loop, pneumatic road tube, piezoelectric cable, and weigh-in-motion system. Drawbacks include the disruption of traffic for installation and repair, failures induced by poor road conditions, and system reinstallation caused by road repairs or resurfaces [2]. Non-Intrusive technology include microwave radar, infrared, Video Image Processing, etc. They are installed above the pavement or on roadside so that the installation and repair of such a system can be done without disrupting the traffic. However, the performance is greatly affected by the environment: confusing signal from sunlight, IR energy is absorbed or scattered by atmospheric particulates, fog, rain and snow. Besides, the devices listed above need auxiliary power supply circuit, which increase the costs and not suitable for distributed in a large scale space.

The increasing traffic congestion is a growing problem in many countries. Motivation for using Wireless Sensor Networks (WSN) to solve the problem needs searching for reliable and cost-effective devices, which can provide traffic data. Magneto Resistance Sensors have received lot of attentions. They are small size, flexibility in deployment configuration, and rarely affected by meteorological environment [3-5].

However, most of proposed research of magneto resistance were based on GMR or AMR, whose performance are limited by the Low-Frequency noise, nonlinear saturation field and low sensitivity for weak magnetic field measurement [6, 7]. There's serious magnetic hysteresis exists in the AMR, so that degaussing circuit are required in the sensor device, which restrict the technique applying widely in WSN apply [8, 9].

This paper presents the design and implementation of a brand new wireless sensor nodes for vehicle detection based on the Tunnelling Magneto Resistance (TMR), manufactured from CMOS-MEMS. The node was designed as an embed system with a microcontroller. The TMRs were used as the sensitive elements in three directions to measure the geomagnetic field of each dimension. Signal conditioning circuit were designed to ensure the analogue signal acquitted accurately. Secondly, An simple aural signal measuring circuit was realized to pre-detecting the vehicle from remote distance by the sound it emitted, so that the main system could in sleep mode for energy saving. Thirdly, an improved ATA detection algorithm was established. By the feature distance between the data series in sample window defined to observe magnetic field change, the algorithm counts the vehicles and schedules the state machine of the system. Outdoor experiments were conducted, the on road testing result shows the node have good performance and suitable for WSN application in ITS.

2 The measuring principle and TMR

2.1 GEOMAGNETIC DETECTION PRINCIPLE

The geomagnetic field is weak, ranged from 0.3 to 0.7Oe, but the magnitude is relative uniform and stable in a square

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area. Since the Magneto conductivity of Iron is far larger than that of the air, ferromagnetic substance would cause a change in a magnetic field, distort the magnetic lines of flux. Since almost all vehicles have significant amounts of ferrous metals in their chassis the magnetic field disturbance created by a vehicle is sufficient to be detected by a magnetic sensor, which makes it a good candidate for detecting vehicles.

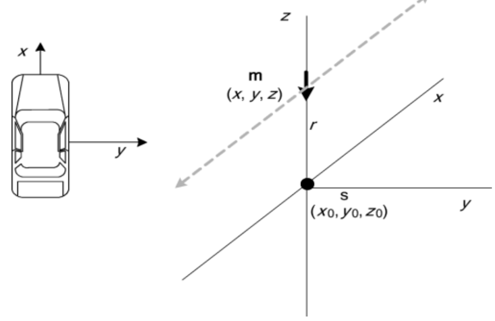


FIGURE 1 magnetic dipole of vehicle moves in x axis

The simplest mathematical model to describe the magnetic signature of a vehicle is a magnetic point dipole with a magnetic moment m cantered in the vehicle and parallel to the Earth's field (Figure 1). The field components B_x, B_y, B_z are

$$B_x = \frac{\mu_0}{4\pi}\frac{m_x(2x^2-y^2-z^2)+3m_y xy+3m_z xz}{r^5}, \quad (1)$$

$$B_y = \frac{\mu_0}{4\pi}\frac{m_y(2y^2-x^2-z^2)+3m_x xy+3m_z xz}{r^5}, \quad (2)$$

$$B_z = \frac{\mu_0}{4\pi}\frac{m_z(2z^2-x^2-y^2)+3m_x xy+3m_y xz}{r^5}, \quad (3)$$

where μ_0 is the permeability of free space, m_x, m_y, and m_z are the magnetic dipole moments in X, Y and Z direction, $s(x_0, y_0, z_0)$ and is the distance from the dipole to the observation point.

Suppose a vehicle moves in the x direction, m_x=m_y=0, the magnetic induction of magnetic dipole B_z is determin-ed by m_z and E_z, *where* E_z is the component of Earth's field in Z direction.

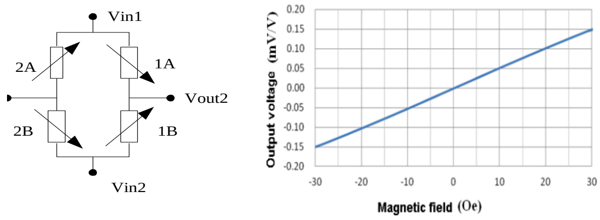
$$B_z = Z_E + \frac{\mu_0}{4\pi}\frac{m_z(2(z-z_0)^2-(x\text{-}x_0)^2)}{\left[(z-z_0)^2-(x-x_0)^2\right]^{\frac{5}{2}}}, \quad (4)$$

where B_Z can be used to judge whether a vehicle pass though the detection area. For each type vehicle may have their own ferrous metal distribution, distinct magnetic signature with multiple peaks they yield is benefit to vehicle recognition.

2.2 TMR SENSOR

TMR was first used in hard disk technology. With the change of external magnetic field, the Magnetic Tunnel Junction (MTJ) generates a change in resistance. Under the applied magnetic field, the magnetization direction of free layer will change, while the pinning layer keep still. So the relative orientation between the two layers is changed, resistance of the MTJ across the insulating layer is observed. Since this physical effect is based on the electron tunnelling effect in insulating layer, it is called as the Tunnelling magneto resistance effect [10].

This used the TMR chip MMLP57F with SOP8 packaging and a Wheatstone bridge inside consists of four pieces of TMR elements. The internal structure and output specific are shown in Figure 2.



a) b)
FIGURE 2 MMLP57F specification: a) Internal structure, b) Output feature in±30Oe

While the external magnetic field is changing, the resistance changing trend of 1A and 1B are opposite to that of 2A and 2B. Assume the four elements have equal resistance R when the detecting field is at zero. Output voltage is:

$$V_{out} = V_{-out1} - V_{-out2} = \left(V_{in1} - V_{in2}\right)\frac{\Delta R}{R}, \quad (5)$$

where V_{in1} and V_{in2} are the bias, ΔR is the absolute value of changes in resistance. The output feature is shown in Figure 2b. Here, bias is 5V, from –30Oe to 30Oe, the sensitivity is 4.8 mV/V/Oe, the nonlinearity less than 1% and the hysteresis error is about 0.1%. That is sufficient to meet the requirement for geomagnetic field detection.

3 Hardwire design of the sensor

3.1 THE STRUCTURE OF NODE

The node is consists of five main units: the acoustic signal detection unit(ASD), the three axis magnetic detection and signal conditioning(MDSC), the wireless transport unit(WTU) and a microcontroller (MCU). The block diagram of the system is presented in Figure 3. The MCU is EFM32G, specially designed for low-power applying [11]. The core of chip is Cortex M3, highest working frequency 32MHz, supports five mode from EM0-EM4 and capable to wake up in 2 µS from sleep mode. Peripherals has the autonomous working ability in CPU sleep duration. The ADC is 8 channel, 12bit, rate at 500K/S with operating current 200µA, which is helpful for high speed data acquisition.

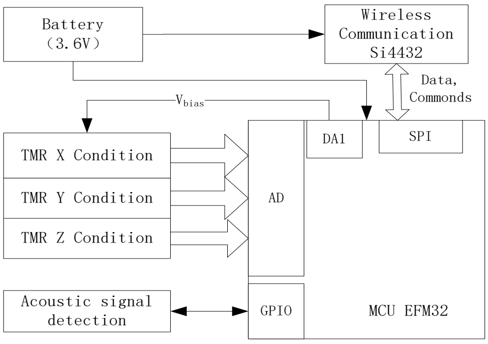


FIGURE 3 The block diagram of the system

Wireless chip Si4432 is used for communication, the bias 3.6V, transmission frequency 900 MHZ, the maximum data transfer rate 256 bps. The diversity antenna, power amplifier, digital modem and a 64B FIFO are internal integrated. External components are one 30MHZ crystal oscillator and a transceiver. The EFM32G communicates to the Si4432 through the SPI interface, the work mode settings and the data are transferred in packets.

3.2 THE MAGNETIC SIGNAL ACQUISITION AND CONDITION

The magnetic induction by vehicles is about -200uT to 200uT, and the responding output range of a single TMR is -32mV to 32mV. So, a power amplifier circuit is considered to conditioning the signal to 2.5V level to satisfy the AD sampling requirement. Since the equivalent internal resistance of TMR bridge is greater, and the magnetic signal to measure is weak, which require the amplifier has high CMRR. The Instrument amplifier chip INA332 can exercise its restraints upon the CMRR and reduce the disturbance from temperature drift and null shift. The chip has low power consumption that meets the system energy management. The conditioning circuit is shown in Figure 4.

The amplifier gain G is calculated from:

$$G = 5 + 5 \cdot \left(\frac{R5}{R6} \right), \tag{6}$$

where, R5=147K, R6=10K, G≈80. Vref=1.25 V. The common mode voltage(CMV) of TMR is 3.3V/2=1.65V. To ensure the input signal have maximized dynamic range, the ADC bias is set to 2.5V.

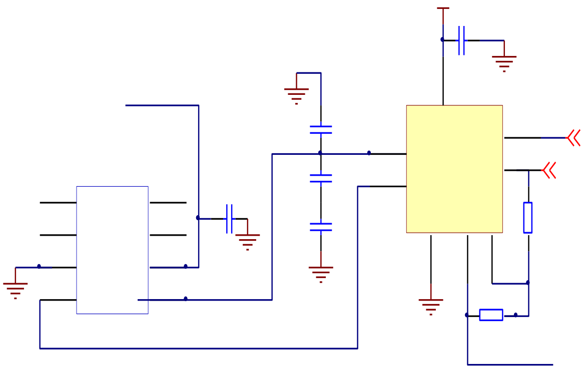


FIGURE 4 The circuit of a single TMR Sensor

Not like other MR chip that should designed with a special power circuit, the three dimension TMR chips are biased by the DA channel of the MCU directly, V_{bias}=3.3V. This is benefit from TMR extremely high input impedance, almost at MΩ level. Meanwhile, MCU provides the power in a intermittent way. The duty time span including the signal setup time and the analogue digital conversion time. For INA332, the AD time is 1µS. The designed circuit limited the amplifier gain under 100, so that operation bandwidth is about to 1MHZ, that minimizes the signal setup time.

3.3 THE ACOUSTIC SIGNAL DETECTION UNIT

To promote energy usage rate, the MCU and magnetic sensor should in speed mode or low power condition in spare time. The acoustic signal detection is used for pre-detecting the audio signals from vehicles, when the threshold is reached, an input is trigged to the MCU, and the system shift into vehicle detecting mode.

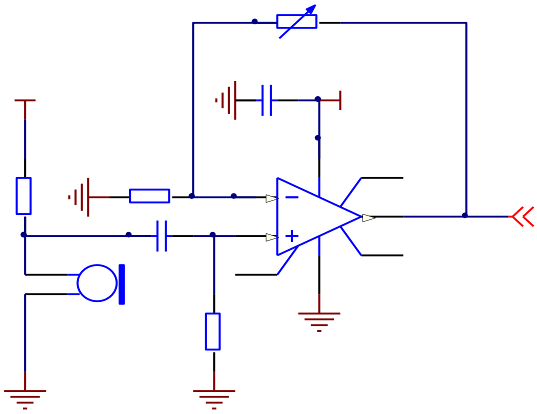


FIGURE 5 The acoustic signal detection circuit

In Figure 5, a two order active amplifier circuit is designned with high pass filtering. The GPIO of MCU have a high driving preferment of 20mA, 3V. External interrupt is supported to wake up the MCU from low power mode (EM1-EM3). The WM-034, an Omni directional electrets microphone has sensitivity of -44dB-36dB. With the in-phase proportion amplifying structure, Op07 magnification is A_{vf}=R4/R2. The range of sensitivity is adjusted by R4, the magnification changed in same way. Generally, the audio frequency the road vehicles emitted between 500HZ to 5KHZ, and that of the background noise is lower than 500HZ. Thus, let the cut-off frequency f_L=500HZ, C1=01.uF, R3=1/2πf_LC1=3.2KΩ.

4 Software design of the sensor

4.1 THE VEHICLE DETECTION ALGORITHM

Jiagen proposed the model of process sensor data in vehicle detection, and based on simple fix threshold value, the Adaptive threshold algorithm (ATA) is applied. But the ATA is not consider of the characteristics of vehicle magnetic signal (VMs), mathematics fault detection may lies in the algorithm. Second, the algorithm require processing on each sample data, which would keep the MCU in busy mode with large emerge consumption [12].

Here, an improved ATA algorithm (IATA) is using in the sensor, the new algorithm can calculate the signal feature between the background window and the current window by separating vehicle coming and leaving events to realize vehicle detection. Based on the energy saving principle in WSN, Duty-cycling policy is applied to decrease energy consuming [13].

The signal characteristic function *I(K)* is used to distinguish the detecting signal from the background signal. Let:

$$I(k) = be^{ak} + c\,, \tag{7}$$

where *ab*>0. The factors may different for different vehicle type at different speed. For two real time signal sequences $X=\{x(1),\ x(2),\ \ldots,\ x(L)\}$, $Y=\{y(1),\ y(2),\ \ldots,\ y(L)\}$; the normalized power series for *I(K)* is:

$$\delta_f(k) = \frac{I(k)}{\sqrt{\sum_{i=1}^{L} I(K)^2}}\,. \tag{8}$$

The feature distance is defined as:

$$D_L(X,Y) = \sum_{i=1}^{L} \delta_f \cdot \left[y(k) - x(k)\right]^2. \tag{9}$$

4.2 THE IMPROVED ATA MODEL

The algorithm flow chart is shown in Figure 6. There are four basic status in IATA: No Vehicle sleep (NVS), High threshold enter (HTE), Middle threshold hold (MTH) and Low threshold leave (LTL). The feature distance used to detect the end point of VMS for HTE and LTL, while Duty-cycling for NVS and MTH.

Let $s(k)$ as current sample series, S_b is the average value of background, *M* is the background windows size.

$$S_b = \frac{S(k) + S(k-1) + \ldots + S(k-M+1)}{M}\,. \tag{10}$$

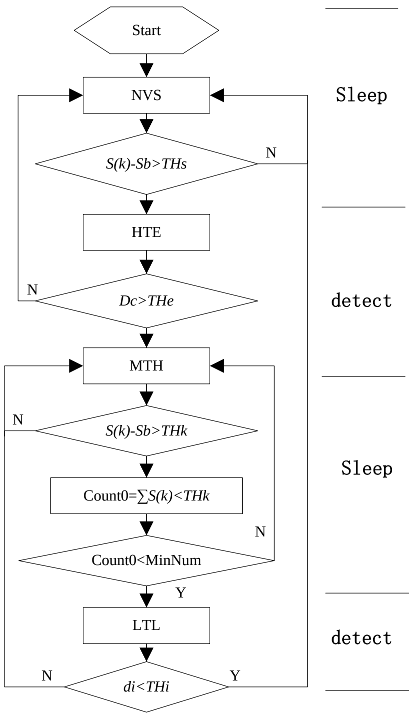


FIGURE 6 The IATA algorithm flow chart

5 Experimental Results and Discussion

The sensor node is in a compact structure, the size is 50mm*50mm, shown in Figure 7. A tiny WSN is built by a Ether2USB device connected to the laptop computer, act as the AP. When the SN is power on, the AP commands are processed in prior, ADC sample rate is set to 100HZ. SN sends a batch of data per second.

5.1 MAGNETIC SIGNATURE OF DIFFERENT PARKING CARS

In this experiment, the Acoustic Unit is Closed. We send AP commands to start the Recording function of SN, by which the SN will upload the raw sample data directly.

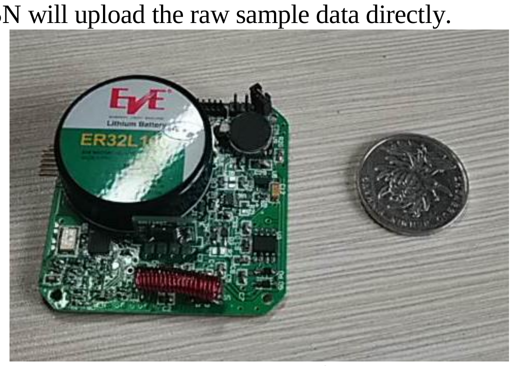


FIGURE 7 The picture of a real SN

We measured on parked vehicles and during parking maneuvers in an outdoor parking area. A compact vehicle (skoda Octavia), a subcompact compact (JinLong) and a truck (GreatWall) were involved. The sensor measured each vehicle on eleven positions along a line centred in the floor of the vehicle (Figure 8d). D1, D2 are the effective detection area from the head and lap of vehicle respective.

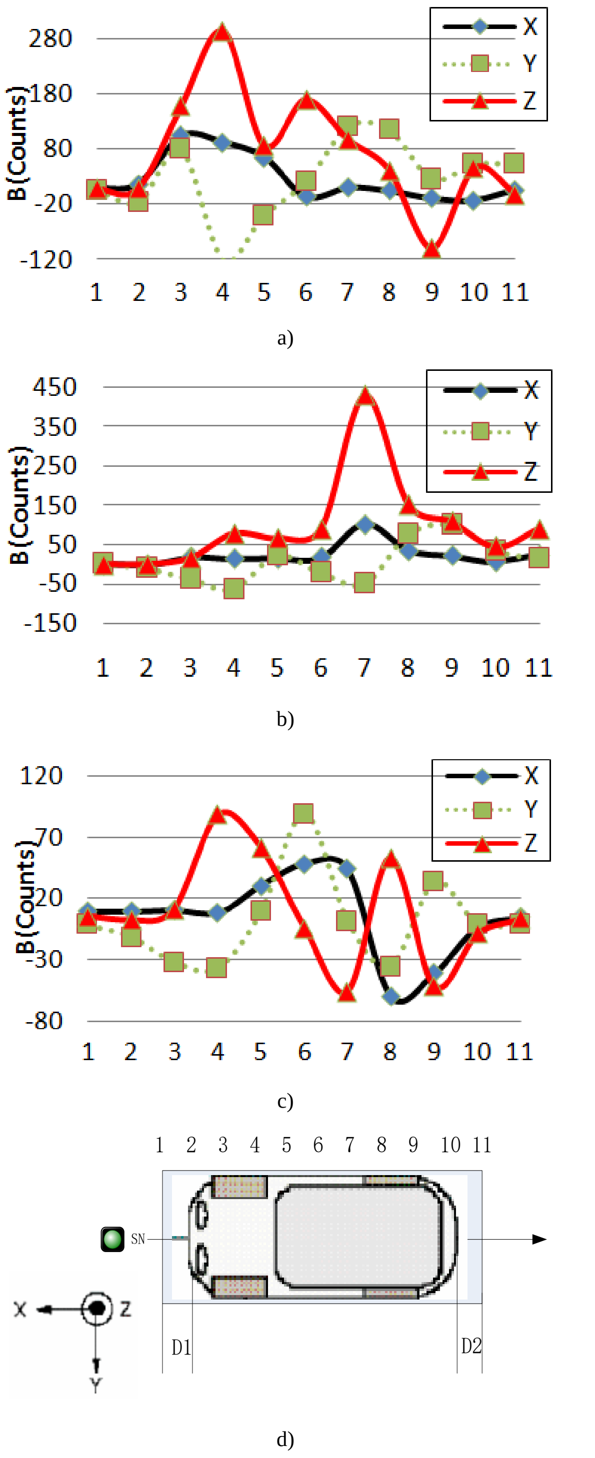


FIGURE 8 Magnetic signature of different parking cars: a) compact vehicle (D1=0.8m, D2=0.6m), b) subcompact vehicle (D1=0.4m, D2=0.3m), c) trunk (D1=0.7mm,D2=0.3mm), d) direction and position

Figure 8(a-c) shows the magnetic induction simultaneously measured by the sensor. Each value is averaged by ten raw data, and the resolution achieved was 36.7nT (12bit), the measurement time was 88mS.

The signatures suggest that compact cars can be roughly described by three magnetic dipoles: two larger dipoles for the engine and wheel axes and a smaller dipole between them. The trunk may have more dipoles with more wheel axes. As to B_Z, the peak counts, peak values and frequencies are distinguished from each type. The B_x and B_y also have distinct features to used for vehicle detecting and movement direction, i.e. the magnetic declination [14].

5.2 ON LINE DETECTING FOR MOVING CARS

The on line test was carried on in a campus lane and a main road to a logistic park. In Table 1, the false and missed count are produced by the IATA detection algorithm and the acoustic detection algorithm respectively. Experiments results shows the average accuracy is 95.8%.

TABLE 1 On line test results

Place	Actual counts	Detected counts	Wakeup times	False	Missed
Lane	86	83	84	1	6
Road	387	394	513	10	3

The magnetic background in campus lane is more stable than the main road, the IATA detection algorithm can had an accurate measurement output. But the missed count in campus is greater than the road, since there the vehicles are most compact type and low speed, if the acoustic threshold not set properly, the MCU would not be trigged when a car passed by slightly. The main road has large flow and through output, and vehicle move at high speed. The acoustic unit trigged about two times than the actual vehicle count because of the noise by adjacent vehicle.

5.3 CONTINUOUS WORKING TIME ESTIMATION

The power consumption of a node is:

$$P = \sum I_{ak} V_{DDK} \,, \tag{11}$$

were, I_{ak} and V_{DDk} is the average current and supply voltage of the unit k.

$$I_{ak} = \frac{t_k}{T} I_k + \left(1 - \frac{t_k}{T}\right) I_s \,, \tag{12}$$

I_s is current consumption in sleep mode, I_k is current consumption in active mode, T is the clock period, t_k is duty time on each cycle.

TABLE 2 Energy consumption of node units

Unit	Mode	V_{DD}	I_k(mA)
MCU	Active	3.6	0.18
	Sleep		9×10^{-4}
MDSC	Active	3.3	0.02
	Stop	0	0
ASD	Active	3	0.3
	Stop		0
WTU	Rx	3.6	18.5
	Tx		30
	adjust		8.5
	Sleep		1×10^{-3}

Assume the road lane vehicle flow is 220 per hour, and the node works autonomously, the nodes are distributed a long distance between each other, where communication channel collision is low probability. Duty cycle of ASD is 1%, miss trigger rate is 15%, a handshake package sent to AP every 5min and listen to the AP broadcasting per seconds. By Table 2, power consumption in 1 day is about 10.8mW. So the battery (9000mAh) would last about 1.5 years with the consideration of other battery loss of 30%.

6 Conclusion

A magnetic sensor node is proposed to detect the vehicles by measuring then changes of the geomagnetic field. When vehicles arrive or depart, the acoustic sensor detects the changes in illumination and wakes up the sensor node. The TMR sensor measure the magnetic field and IATA algorithm processes the data with energy saving policy of Duty-cycling is building in the control software. Experimental results showed the node can provide fast detection. The Node is compact, low-cost, and very low-power vehicle detector for WSN applications, and that is also reliable and easy to install and maintain.

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