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MEMS SENSOR IN INTELLIGENT TYRE PRESSURE MONITORING SYSTEM

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ABSTRAK *: Penggunaan penderia tekanan sistem mikroelektromekanik (MEMS) dalam sistem pemantauan tekanan tayar (TPMS) diperihalkan dalam kertas kerja ini. Kajian ini melibatkan analisis data pengesanan MEMS yang menyumbang secara signifikan ke arah peningkatan keupayaan TPMS. Penerangan tentang penderia, teori pengoperasian, prototaip TPMS terpasang dan analisis data ujikaji dibentangkan secara terperinci dalam kertas kerja ini. Untuk tujuan ujikaji, perolehan data dilakukan terhadap prototaip TPMS pintar yang dipasangkan pada rim tayar. Pemeriksaan ambang dilakukan untuk mendapatkan data tentang tekanan dan suhu tayar. Set maklumat yang lengkap untuk keempat-empat tayar yang merangkumi bacaan tekanan dan suhu, isyarat keracak penerima (receiver wake-up signal), pengepala (header), pengenalan tayar (tyre ID), semak-jumlah (check sum), dan mesej tamat (end of message) dalam penerima TPMS turut dianalisis. Hasil yang diperolehi daripada ujikaji tersebut berjaya mengesahkan kebolehgunaan penderia MEMS dalam TPMS.*

ABSTRACT : The use of a micro electromechanical system (MEMS) pressure sensor in an intelligent tyre pressure monitoring system (TPMS) is described in this paper. The study involves the analysis of the MEMS sensory data that contributes significantly towards the enhancement of the TPMS. A detailed overview on the sensor, theory of operation, the assembled TPMS prototype and experimental data analysis were presented in this paper. For the purpose of this experimental study, data acquisition was performed on the intelligent prototype TPMS that was fitted on to a tyre rim. Threshold check was used to acquire the TPM output signal on tyre pressure and temperature data. A complete set of information for all four tyres comprising the measured pressure, temperature, receiver wake-up signal, header, tyre ID, checksum, and end of message in the TPMS receiver were also analyzed. Results obtained from the experiments have successfully validated the usefulness of the MEMS sensor in a TPMS.

KEYWORDS : MEMS, TPMS, Sensor, Sensor Mounting

INTRODUCTION

To date, a wide variety of sensor technology has been deployed by the automotive industry in view of enhancing safety and reliability. The tyre pressure monitoring system (TPMS) that utilises sensor technology is currently an important research domain in the automotive industry. Apart from functioning as a safety device, a TPMS can increase tyre life cycle, reduce fuel consumption and improve gas mileage (Burgess, 2003). Tyres that are accurately inflated will ensure shortest braking distance, reduce blowouts and mitigate hydroplaning for better road handling. On the other hand, under and over inflated tyres may cause abnormal tyre wear, increase fuel consumption, reduce riding comfort and tyre life (Ronald, 1989).

Burgess (2004) forecasted by the year 2010, two-third of the world automotive will be equipped with TPMS, as depicted in Figure 1.The adoption of intelligent tyres with TPMS capability is inevitable as it enables drivers to be aware of a run-flat condition; the period of tyre usage and driving beyond the rated speed. The term 'intelligent tyre' implies an active essential part of the vehicle that contributes on safety security and driving comfort. In addition, TPMS also provides an early warning to the driver on pressure loss, tyre running at low pressure, tyre failure, inflating tyres and location of wheels (Burgess, 2003; CAN newsletter, 2003).

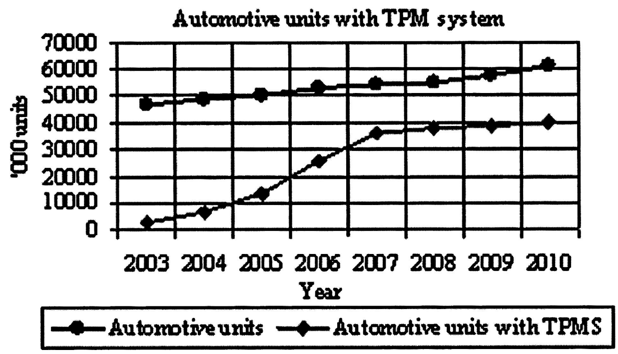

Figure 1. *Forecasted projection of automotive units with TPMS (Burgess, 2004)*

A number of TPMS and its sensor technologies have been widely investigated through experiment and data analysis which include antenna based TPMS, surface acoustic wave transponder, touch mode radio frequency identification (RFID) and crystal based quartz resonator remote sensor (Wunderlich *et al,* 1999; Schimetta *et al,* 2001; Yamamoto *et al,* 2002). Factors such as limitation in the life cycle of the lithium battery, malfunctioning of the electromagnetic RF transceiver unit and the huge echo noise due to broadcasting pulse response through the same antenna are some of the major concerns.

Various types of sensors such as acoustic sensor, optical sensor, vibrating string sensor, ultra wide band technology and capacitive sensor have been widely used in the research (Rainer, 1999; Daimler, 2005). These sensors have the potential to detect data on road condition that can be used to derive friction parameters, but not for force measurement (Schimetta *et al,* 2000; Scholl *et al,* 2003). The main disadvantage of these sensors is low robustness in a harsh environment during vehicle operation, not withstanding the fact that the TPMS technology is still improving and its sensors are becoming more robust. Nevertheless, the appropriate sensors for different applications of TPMS are still being investigated and discussed.

In order to meet the challenges of TPMS within the sensor limited capability factor, extensive experiments and analysis on the sensor technologies have been carried out. Results from the study by Gogoi and Mladenvic (2002) and Quero and Brey (2002) showed that the capacitive MEMS sensor has the greatest potential for use in the development of automotive intelligent safety system. Apart from its ability to be integrated into a complete electronics system, robustness, small size and low power consumption are some of the significant features of the MEMS sensor. Thus, the capacitive MEMS sensor technology opens up a new perspective for an intelligent automotive safety system and perfectly fulfils the requirements on high robustness, low power consumption, other than cost benefits.

Hence, the objective of this paper is to report the experimental results of a surface micro-machined capacitive MEMS sensor on the TPM module, which is based on the Motorola MPXY8000 (Masi, 2004). Sensing signal to the TPMS using the threshold check was acquired from the data acquisition environment of the MEMS sensor. A complete set of receiver's output signal on pressure and temperature of the four tyres or the so-called intelligent tyres are demonstrated in the form of 1 and 0 hexadecimal numbers. The paper also provides an overview of the TPM module, theory of principle operation, method of sensor data acquisition, the TPM prototype development and discussions on the experimental results.

SENSOR OVERVIEW

The TPMS constitutes a tyre pressure module (TPM) and a receiver unit. The TPM module consists of a micro-machined capacitive MEMS sensor, microcontroller unit (MCU), transmitter and a printed copper loop antenna in a single die that resides within the tyres. The receiver unit includes an antenna, a romeo2 UHF receiver and a serial peripheral interface (SPI). However, in this section, discussions are limited to features and application, pin function and serial interface description of MEMS sensor.

Features and Application

In this cutting edge product, the TPMS MEMS sensor critical design parameters include the following major features and application:

- Dedicated to transmit pressure and temperature at a range of up to 637.5 kPa and -40 to +150 °C respectively, securing data protocol through 433.92 MHz.
- MEMS surface micromachined P-cell pressure and temperature sensor interfaced with wake-up feature, all on a single die.
- 2.1 to 3.6 V operating voltage and low power consumption for extended battery life.
- 8 bit digital output for both pressure and temperature and optimized for MC68HC908RF2 interfacing.
- SSOP (small shrink outline package) pressure sensor package with integrated media protection and also integrated low frequency oscillator with MCU wake up.
- Ideal for integration with existing remote keyless entry systems and 3-second wake-up for module level energy management.

The MEMS pressure sensor is perfect for smart TPMS with regard to providing low cost bidirectional communication transponder applications. The device can be used for various applications in the automotive industry. In TPMS application, the MEMS sensor involves a wireless operation and was used to monitor tyre pressure and temperature so as to reduce potential blowout situation and damage to personnel and vehicle. The monitored data are also displayed to provide information to the driver that can help prevent accidents as well as enhancing fuel economy and extending tread life. In addition, it provides real-time activation of both visual and audible warning signals to indicate abnormal tyre condition. Moreover the following factors are identified in favour of the MEMS sensor such as size, costs, system mounting and integration, robustness, stability over life time, low power consumption and better signal conditioning against EMC.

Pin Function

The proposed MEMS sensor comprises six I/O pins and two power supply pins, namely V_{DD} and V_{SS}. There are four input pins S0, S1, DATA, and CLK whilst the other two are output pins, which are OUT and RST (Burgess 2002). The pin assignment and function descriptions are shown in Figure 2 and Table 1, respectively.

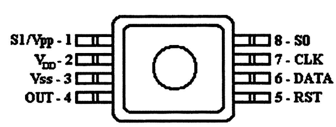

Figure 2. *Pin assignment of the sensor (Burgess, 2002).*

Power is supplied to the sensor through V_{DD} and V_{SS} pins. A surface mount of 0.1µF capacitor is mounted close to the V_{DD} and V_{SS} pins to avoid decoupled noise and to provide accurate reading. The operating modes of the sensor are established via control setting of pins S1 and S0. The MEMS sensor and the controller communicate through the CLK and DATA pins. The CLK pin is employed to provide a clock for loading and shifting data at a maximum frequency of 1 MHz into the DATA pin. The DATA pin is the serial data in function for setting the threshold of the voltage comparator. The CLK and DATA pins contain an internal Schmitt trigger to improve noise immunity and to avoid undesired shifting by keeping the signal from the MCU idle in the low state.

Depending on the mode of control, the OUT pin serves three functions such as output read mode, standby/reset mode and IRQ pin connection. In output read mode, the OUT pin is connected to the analog comparator for sensor acquisition and it is set to high if the DAC output is lower than the sampled value in the sampling capacitor, and vice versa. During standby/reset mode, the output multiplexer connects the OUT pin to an active low wake-up pulse signal to wake up an MCU in stop mode. This low pulse is generated from the internal low frequency oscillator (LFO) and the divider chain. With the nominal frequency of the internal LFO at 5.4 kHz, the wake up pulse occurs approximately every 3 seconds. The OUT pin can be connected to an IRQ pin that supports wake up from idle or stop. Before initiating the standby mode on the MCU, the IRQ pin needs to be configured as an interrupt pin to wake up the MCU on a falling edge. The RST pin is an output pin that serves as a periodic low-pulse reset, which triggers a signal approximately every 52 minutes to the microcontroller reset pin. Normally, a TPMS includes a watchdog timer to safeguard the system from crashing by applying a reset signal (Burgess 2004).

Table 1. Sensor pin description and functions

	Pin Name	Pin Function	Direction
1	S1/V_{PP}	Mode Select	Input
2	V_{DD}	Positive Power	Power
3	V_{SS}	Ground	Power
4	OUT	Comparator or Wake-up Output	Output
5	RST	MCU Reset	Output
6	DATA	Data	Input
7	CLK	Data Clock	Input
8	S0	Mode Select	Input

Serial Interface Description

At standby/reset and output read modes, the SPI loads data into the DAR of the MEMS sensor. During the loading, the MCU becomes the master whereas the MEMS sensor becomes the slave and the data transmission is unidirectional from the controller to the sensor. The data to be clocked in by MCU or controller must be synchronized with the SPI of the MEMS sensor, prior to data being clocked into the DAR. For MCUs without SPI, one needs to use software routines to emulate the SPI protocol. One must also ensure that the MEMS sensor's internal SPI bit counter is synchronized with the data that is being shifted.

During power up, this bit counter defaults to an unknown state. The bit counter resets to zero when entering into either the measured pressure or measured temperature modes. This counter reset provides a convenient method for providing one hundred percent assurance that the data shifted in is always synchronized with the DAR bit counter (Burgess, 2002).

THEORY OF SENSOR OPERATION

The micro-machined capacitive MEMS pressure sensor cell with an integrated temperature sensor and interface circuit is bonded together in a single SSOP package for smart-sensing and bidirectional communication applications. The device is able to measure absolute pressures and temperature with MCU control and converts these values to 8-bit digital value using successive approximation (Burgess, 2002). The device also includes MCU wake-up and periodic reset features controlled by an internal LFO. The main part of the sensor consists of two circuits. The first circuit consists of the pressure and temperature sensors. This circuit is fully analog and has two status pins $S1/V_{PP}$ and S0 to determine which one is active. The sensed value is converted into a voltage, which is subsequently stored in the sampling capacitor.

The other circuit of the sensor is a mixed-signal, with a digital input and an analog output. The input is taken through the CLK and DATA pins using a simple serial communication protocol. The data is stored in the D/A register and converted to a DC voltage. This voltage is then compared to the voltage stored on the sampling capacitor to determine the state of the OUT pin using a successive approximation algorithm. Eight successive data are used to yield an 8-bit digital value for comparison purpose. The basic operating function of the receiver is fully compatible with the TPMS module.

A wake-up facility is also available where a signal is sent to the MCU from the OUT pin every 3 seconds. When the MCU of the TPM module decides to transfer the data frame, it wakes up the receiver. After 10 successive wake ups (approximately 30 sec), the module transmits its status in hexadecimal form of the data frame to the receiver as well as a reset signal on the

RST pin. Once the receiver detects the data frame (preamble, device ID, pressure, temperature, status, checksum and stop bits), it sends out all the following data to the SPI for monitoring. The sensor operation is dependent on the mode of operation and the data acquisition process (Daimler, 2003).

Mode of Operation

There are four available operating modes for the MEMS sensor, which are standby/reset, measure pressure, measure temperature and output read. The mode of control can be selected by setting the control pins of S1 and S0 as summarized in Table 2 shown below.

Table 2. Mode of control of pin S1 and S0

S1	S0	Mode
0	0	Standby/reset (Idle)
0	1	Measure pressure
1	0	Measure temperature
1	1	Output read

In standby mode, the analog sections of the sensor are switched off, but LFO, SPI, DAR, wake-up pulse and reset pulse dividers are all switched on. The controller can shift threshold data into the DAR register and sends a 370 μs wake-up pulse through OUT pin approximately in 3 seconds intervals. In pressure measurement mode, the sensor multiplexer connects the output of the pressure sensor to the sampling capacitor. In order to allow the pressure sensor switched capacitor circuit to turn on and stabilize, the duration of delay should be at least 500 μs. A delay of at least 500 μs avoids sampling of the pressure sensor output while the circuitry is still unstable.

In temperature measurement mode, the sensor multiplexer connects the output of the temperature sensor to the sampling capacitor. The circuit needs at least 200 μs to stabilize from initiation. The bit counter is reset during pressure and temperature measurement mode, thus allowing synchronization with the external clock at the CLK pin. In output read mode, the output multiplexer connects the comparator output to the OUT pin. Upon completion of sampling from the pressure and temperature sensor, the mode is initiated and immediately sampling of the OUT pin will take place or successive approximation routine will be performed before the sensor voltage in the sampling capacitor is discharged. In this mode, the sampled sensor voltage may be converted to an 8-bit value or a threshold check may be initiated (Agic, 2005).

Sensor Data Acquisition

Data can be acquired from the sensor using a successive approximation algorithm or a threshold check. A successive approximation provides an accurate conversion of the sampled temperature or pressure reading into an 8-bit value. In the threshold check, the DAR is preloaded with a threshold value during standby/reset mode to detect whether the pressure or temperature has crossed a particular level. The following section describes these two methods in detail.

During analog to digital conversion, the MCU is used as a successive approximation routine (SAR) controller. The 8-bit DAC data is loaded serially into the DAR by the MCU for each of the eight guesses. Therefore, a complete successive approximation conversion is completed in eight guesses with eight CLK cycles per guess, or 64 CLK cycles. The process of monitoring the OUT pin and setting or clearing bit by bit in the SAR is performed until all eight guesses (8 bits) are determined. Soon after the guess is loaded and if the state of the OUT pin is low, then the guess in the DAR is equal or greater than the value in the sampling capacitor. If the OUT pin remains high, then this implies that the guess is too low.

Threshold check is the process to estimate whether the pressure or temperature is above or below a particular level without having to perform a full successive approximation routine. Several thresholds can be set to check the range of pressure or temperatures. When performing a threshold check, the DAR can be preloaded with a threshold value during standby/reset mode. The sensor output is then appropriately sampled and compared to the threshold value during output read mode.

METHODOLOGY

TPM prototype development

The TPM prototype that was fitted on to the tyre rim comprised the sensor assembly and its mounting. The MEMS sensor will be operating in a harsh environment due to vibration, weather, moisture and impacts. Even at a normal speed, the level of vibration can be sufficiently high to cause device failure to the sensor module. These sensors must be attached on to a special mounting that will hold the sensor module while protecting them from the harsh environment. At the same time, the sensor needs to be exposed to air pressure. It is therefore necessary for the mounting to be designed as a housing to the sensors. Selecting the right materials for the sensor is crucial in enhancing the performance and reliability of the TPM module.

There are generally two concepts for mounting sensors on to the tyre rims namely mounting on the tyre rim and mounting on the stem valve (Agic, 2005). Mounting on to the tyre rim would require the sensor module to be assembled facing the mounting, for purposes of protection against the external environment. Mounting on the stem valve on the other hand, requires an assembly that combines the stem valve and the mounting at the external rim. In the latter, the sensor will be inserted from the side of the tyre and be part of the stem valve. For the purpose of this prototype development, the MEMs sensor is inverted and screwed to the mounting. The module is then attached to the tire rim using a nylon strap and tightened with a clip.

The design and dimensioning of the mounting that holds the sensor assembly is as shown in Figure 3. The geometry and dimensions are critical since the height of the mounting and the sensor module when fitted on to the tyre rim shall not exceed the highest tip of the tire rim. Otherwise, friction may occur between the tyre and the TPM module. It is also necessary for the back of the mounting to be slightly curved to accommodate the shape of the tyre rim so that the mounting will fit snugly in the drop centre of a 15-inch rim. For the purpose of the prototype, the mounting was fabricated from hard epoxy material that can withstand high temperature. The complete assembly of the TPM prototype is shown in Figure 4.

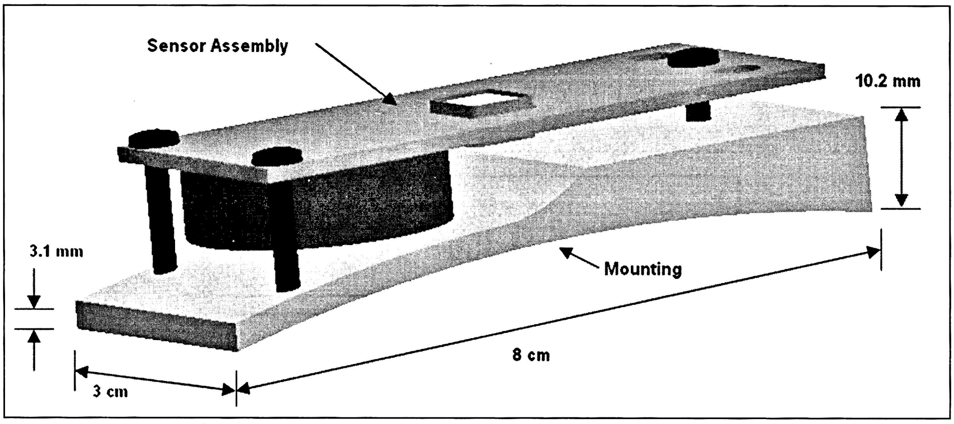

Figure 3. *Schematic representation of the TPMS prototype comprising the sensor assembly and mounting*

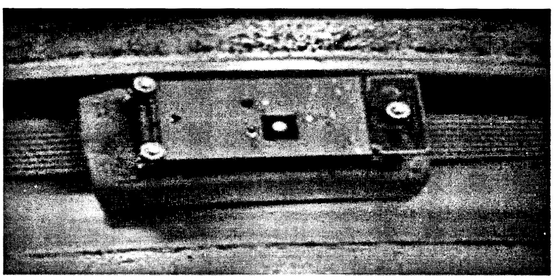

Figure 4. *The TPMS prototype fitted on a tyre rim*

EXPERIMENTAL RESULTS AND DISCUSSION

In the prototype, a loop antenna transmits the tyre pressure signals from the module to the receiver. The acquisition of signals is then carried out using Agilent 54622D Mixed-Signal Oscilloscope. The data is available by changing the threshold value of the sensor in MCU. The acquired data helps in the evaluation of the testing process and performance of the MEMS sensor measurement.

Figure 5 shows the output of MEMS sensor from OUT pin at various modes. In the standby mode, the analog sections of the sensor are switched off and only LFO, SPI and DAR are switched on to generate wake up pulse. The wake up signal at standby mode is approximately 3 sec interval as shown in figure 5 (a). Figure 5 (b) and 5 (c) show the output signals when OUT pin is connected to the analog comparator for the sensor acquisition during output read mode. When the DAC output from DAR is higher than the sampled value in the sampling capacitor i.e. DAC > sampled sensor voltage, the output of OUT pin is low indicated by a logic 0 as shown in figure 5(b). On the other hand, if the DAC output is lower than the sampled value in the sampling capacitor, the OUT pin is high indicated by logic 1 as shown in Figure 5(c). Thus, the sensor monitors and transmits the tyre pressure to the receiver whether low or high compared to with threshold pressure.

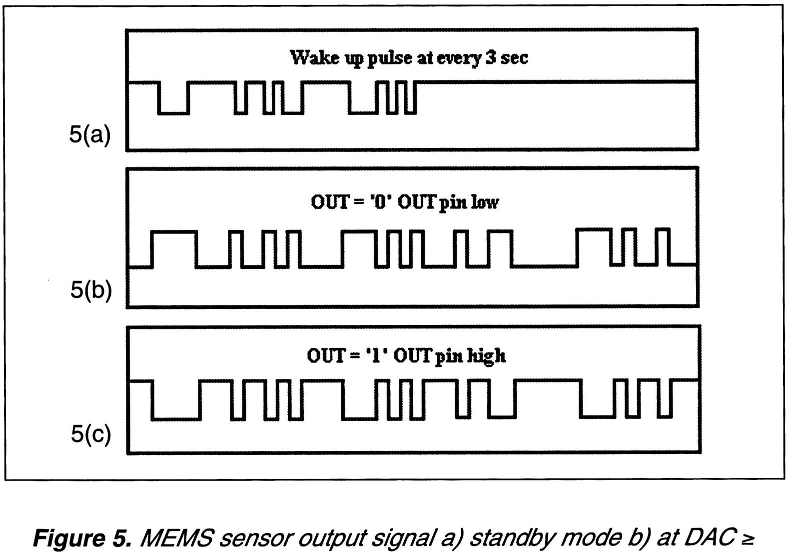

Figure 5. *MEMS sensor output signal a) standby mode b) at DAC ≥ sampled sensor voltage c) at DAC < sampled sensor voltage*

Figure 6 indicates the complete sets messages of four tyres in the form of 1 and 0 hexadecimal numbers. Each tyre has different 1 and 0 logic implying different ID as well as different pressure and temperature.

Figure 6. *Complete messages of tyre pressure and temperature*

The TPM data frame is transmitted to the receiver, which includes the temperature and pressure, as well as the receiver wake-up signal, header, tyre ID, checksum, and end of message with a very simple protocol for communication. Before programming the RF2 receiver for TPMS usage, each tyre should be set up with its own unique ID code so that the receiver can distinguish it from the others. Once receiver is awakened, it detects the tone using a continuous Manchester-encoded bit stream. Manchester encoding is a digital signal whose value transitions between high and low halfway through each bit period i.e. data is sent during the first half-bit, complementary data is sent during the second half-bit. It can detect and demodulate the signal, send out only important data of ID, temperature, pressure and checksum to the SPI. The frame ends with an end of message (EOM) signal that consists of two consecutive NRZ 1's or 0's.

CONCLUSION

In this paper, a framework of MEMS sensor used in the TPMS tyre module and data acquisition of tyre pressure and temperature has been presented. The implementation of the MEMS sensor incorporating the prototype of a TPM mounted on the intelligent tyre rim is explored for its data analysis. The importance of the mounting that holds the MEMS sensor has been emphasized in this paper together with its design details for the TPM prototype. Measurement and acquisition of experimental data from the mounted TPM and the receiver were carried out using the Agilent 54622D Mixed-Signal Oscilloscope. The experimental analysis showed that the output signals from the TPM transmit signals based on the sampled value in the sampling capacitor i.e. real pressure inside the tyre and the TPMS receiver provides a complete set of information on tyre pressure and temperature. Results obtained from the MEMS sensor to the TPMS receiver have been successful through transmitting tyre pressure and temperature. Further work in this area will include improving the design and material of the mounting for purposes of enhancing the life cycle of the TPM module.

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