TYRE PRESSURE MONITORING SYSTEM

By

EDZUAN BIN OMAR

FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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December 2005

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Edzuan bin Omar

ABSTRACT

Maintaining the correct tyre pressure for a vehicle is the variable in how much load its tyres can safely carry. The correct pressure will carry the weight without a problem. Too little tyre pressure will eventually cause catastrophic tyre failure. This project requires student to study the existing system of TPMS and if possible to come up with depth research on how to design the system from scratch. This project is the initial background work for the development of a miniature pressure sensor and controller unit for TPMS. The main purpose of these systems is to warn the driver if their tyres are losing air pressure, leaving the tyres under inflated and dangerous. The systems attach a pressure sensor together with transmitter to the vehicle's wheel inside the tyre's air chamber. The final objective of the continuous project is to design a circuit consists of pressure sensor, microcontroller (PIC), transmitter and receiver. The pressure sensor used is a microelectronic device. This system will read a pressure inside the tyre and transmit it to the receiver which can produce the output (display). This report represents approaches to the scope of developing the MEMS pressure sensor which used in TPMS. The methodology divided by two; TPMS methodology and MEMS pressure sensor methodology. For the TPMS methodology, input from pressure sensor is required before a transmitter unit transmits the data to a receiver and displays the value of the pressure. For the MEMS methodology, it was divided into mechanical and electrical design elements. Mostly the related information is collected from reference books and from internet. As for the conclusion tyre pressure monitoring system is an interesting area of focus and opens up a new field of technology and creative thinking.

ACKNOWLEDGEMENTS

Using this opportunity, the author would like to express gratitude to all that have been assisting in completing this project. Profound appreciation and sincere thanks goes to my supervisor, Ms. Illani Binti Mohd Nawi for all the tremendous effort given in assisting and guiding throughout conducting this project. Million thanks to laboratory technicians, especially Ms. Siti Hawa of Electrical and Electronic department for assistant and co-operation given are highly appreciated. Not forgetting to all Electrical and Electronic lectures, thank you for those that have been helpful and resourceful in assisting performing this project. Last but not least, the author would like to thank all colleagues, friends and especially my family who have helped me along the way. Again, thank you all!

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LIST OF ABBREVIATIONS

MEMS	Microelectromechanical Systems
ECU	Electrical Control Unit
TPMS	Tyre Pressure Monitoring System
MCU	Microcontroller Unit
TPMM	Tyre Pressure Monitoring Module
LF	Low Frequency
S/TX	Sensor/Transmitter

CHAPTER 1
INTRODUCTION

1.1 Background of Study

A direct tyre pressure monitoring system requires a very long battery life; 7 to 10 years. Because the battery resides inside the tyre, a heavy, bulky battery is not an option. The frequency of measurements and transmissions must be carefully considered. In addition, low power consumption components must be chosen. The environment inside a tyre is very high pressured. The electronic products and silicon pressure sensors is sensitive to some extreme conditions or environment exposed to the air. Medium protection is vital to a product's survival, as well as thermal characteristics.

Most auto manufacturers now require a 7 to 10 year operational lifetime for a TPM module [1]. To meet this requirement, each component must have a very low current standby or idle mode, as well as efficient measurement and transmission hardware. The control algorithm should limit measurements and transmissions to as infrequently as possible. Compounding on the power consumption issue, a heavy, bulky battery is simply not an option. Usually the entire module including the electronics PCB, housing, and mounting hardware needs to be below 30 to 40 grams to avoid an out-of-balance tyre [1].

Inside the tyre is a very harsh environment, with possible temperatures from -40 to +125°C, and exposure to moisture, tyre mounting grease, and a variety of other potentially corrosive materials. Careful package design is necessary to allow a broad temperature range and robust media compatibility. As with practically all automotive applications, cost is a major issue. Integrating the functionality of the TPMS and the remote keyless entry (RKE) receiver can help to reduce the overall system cost. Also, smaller, more highly integrated components to reduce board space can present significant savings.

1.2 Problem Statement

The aim of this project is to initiate a startup research to produce the so-called Tyre Pressure Monitoring Systems (TPMS) that able to perform tyre pressure monitoring. Tyre Pressure Monitoring Systems (TPMS) is a way of warning a driver that a tyre is under inflation which could decrease the performance of the vehicle and increase the risk of crashing. It is difficult to spot an under inflation tyre visually, especially without a fully inflated tyre as comparison. Due to the inflexibility of current tyre walls a drop in pressure will only lead to slight slump when the tyre is viewed at rest; whereas when car is in motion, the tyre looks absolutely normal. This is why TPMS can be useful as it can warn drivers that their vehicle has an under inflated tyre despite the tyre looking perfectly normal. There are many dangers to having under inflated tyres because they are designed for use at their recommended pressure. Under inflation can lead to deformation in the tyre wall, which reduces the amount of surface contact the tyre has with the road. This can have many consequences:

i. Reduces handling characteristics and reduced control of the vehicle.

ii. Longer stopping distances

iii. Higher chance of the tyre delaminating especially in the wet, which could lead to a sudden tyre failure.

The current TPMS has few factors being taken into consideration; namely:

i. **Convenience** - Full-time tyre monitoring means you can check your tyre pressures from the safety and comfort of the driver's seat. It also reduces the possibility of time-consuming tyre repairs.

ii. **Safety** - Incorrect tyre pressures can compromise the stability of a vehicle, its handling and braking and, in extreme cases, could contribute to an accident. Also, most non-crash auto fatalities occur while drivers are changing flat tyres.

iii. **Fuel economy** – Under inflated tyres are costing you money. According to the Society of Automotive Engineers, a tyre with an inflation level just two psi below the optimum level measurably increases fuel consumption

iv. **Protection** - Tyre monitoring protects against damage to expensive tyres and wheels.

v. **Performance** - When tyre pressure is kept at proper levels, optimum vehicle braking, steering, handling and stability are realized.

1.3 Objective and Scope of Study

The objectives of the project are:

- Research on existing tyre pressure monitoring systems which use microelectronic sensor.
- Study on behaviors of transmitter and receiver inside the tyre pressure monitoring system.
- To startup an initial research on how to develop a TPMS; with hope that the continuation of this project will focus on the development of a TPMS; focusing on the miniature pressure sensor to be used in TPMS.
- To develop a step-by-step approach on developing miniature sensor; such as pressure sensor and can be extended to other types of sensor like the temperature sensor.
- To provide a safety system that can be used in automotive industrial.

The scope of study is presented in this report. There are several topics and issue that must be considered before proceeding any further in the design of the system. The scope of study depends mainly on these few areas:

- The design method for TPMS and MEMS sensor.
- The sensor electronic interface, the communication between transmitter and receiver and display unit.
- Study on the MEMS technology pressure sensor and material that being used.

This report will show advantages of TPMS. The current theoretical foundations and case study for tyre pressure monitoring system are available in literature review. The development of the TPMS in precise; pressure sensor and controlling unit is presented in methodology. The findings, design method, materials and extra woks are presented in discussion.

CHAPTER 2
LITERATURE REVIEW

2.1 Description of the Pressure-Sensor Based TPMS Evaluated

Nowadays, tyre pressure monitoring becomes very desirable on automotive market. The sensor/transmitter placed inside the tyre whilst the receiver inside the car (**Figure 1**). Based on the research, six Pressure Sensor Based systems were evaluated [2]. The Pressure Sensor Based systems tested had a pressure sensor mounted either in each tyre or on the valve stem or wheel. The sensors communicated with the receiver through radio waves [2]. Each sensor had a unique digital identification code so that the particular tyre with low pressure could be identified on the driver's display. The digital identification code also prevented signals from other vehicles' sensors from being analyzed by the TPMS [2].

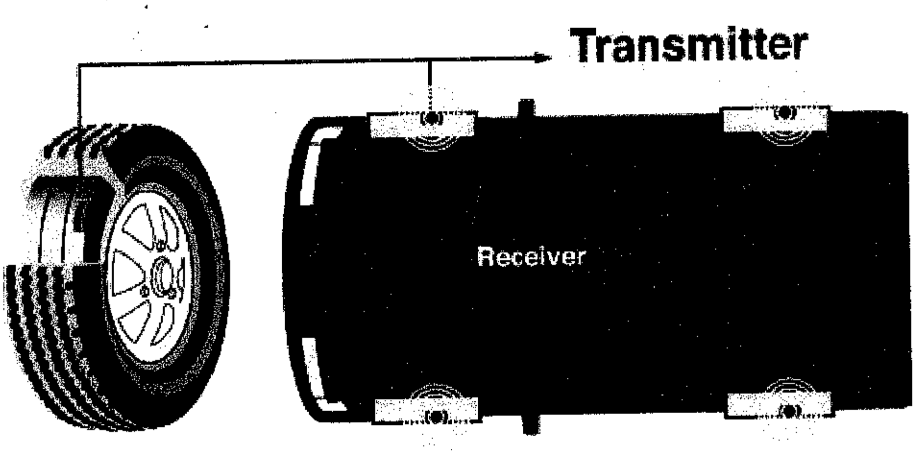


Figure 1 Overview on the Tyre Pressure Monitoring System [3]

2.2 Case Study

Six of the companies that use the pressure sensor based in their TPMS are discussed here.

2.2.1 Beru "Tyre Pressure Monitoring System"

This system was an original equipment pressure-sensor based TPMS. The sensor, which measured both tyre pressure and air temperature, was inserted inside the wheel rim with a threaded aluminum valve stem replacing the original tyre valve stem (**Figure 2**). Each sensor had its own identifying code. The vehicle manufacturer mounted the antennas in each of the wheel well, which were then connected to the vehicle's ECU [2].

The stated accuracy of the system was ± 1 psi [2]. Pressures are sampled by the system every 3 seconds but are transmitted every 54 seconds. In the case of a rapid loss of pressure, the system had the ability to cause the sensor to sample and transmit every 0.8 seconds. The temperature measurement was used to calculate the equivalent cold inflation pressure.

The driver interface for this system is shown in **Figure 3.** The system present on the European specification vehicle provided for testing had a single level of warning. This single warning level indicated the condition of significant tyre underinflation and consisted of the text message "TYREPRESS" followed by either "FRONT" or REAR" and then "L." or "R." to indicate the specific tyre that the warning referred to. The system used pre-stored values to evaluate tyre pressure, but could also accept values supplied by the driver.

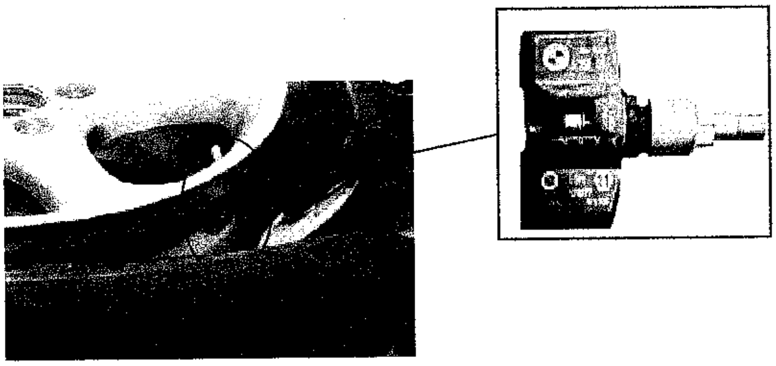


Figure 2 Tyre sensor –Transmitter [2]

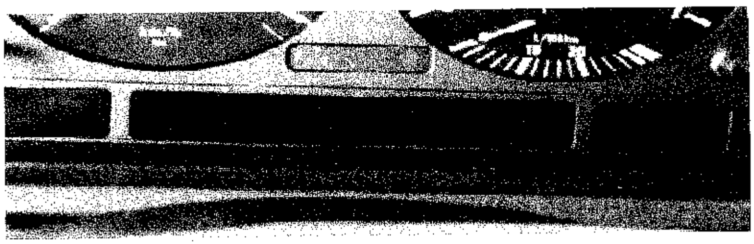


Figure 3 Beru's TPMS warning Message with Wheel Location [2]

2.2.2 Cycloid Co.

The system was a prototype pressure-sensor based TPMS and tyre inflation maintenance system. Tyre pressures were sampled every 30 seconds and the status was transmitted every 1 minutes. The stated accuracy of the system was ± 1 psi. The pressure sensor, transmitter, and inertial driven pump are all contained in a sensor body that mounts to the center of the wheel (**Figure 4**). A special one-way pressure port was installed in a hole drilled through the wheel rim by the system manufacturer [2]. This port was then connected to the sensor/pump mechanism with a rubber hose. The hose allowed the hockey-puck sized sensor/pump unit to monitor current tyre pressure and to pump additional air into the tyres. An example of the inflation capabilities of this system can be seen in **Appendix A.** This system was designed to give two warning levels. The first was a "low pressure warning" designed to activate at 18 psi. The second was a "severe underinflation alert", which was designed to activate at 10 psi.

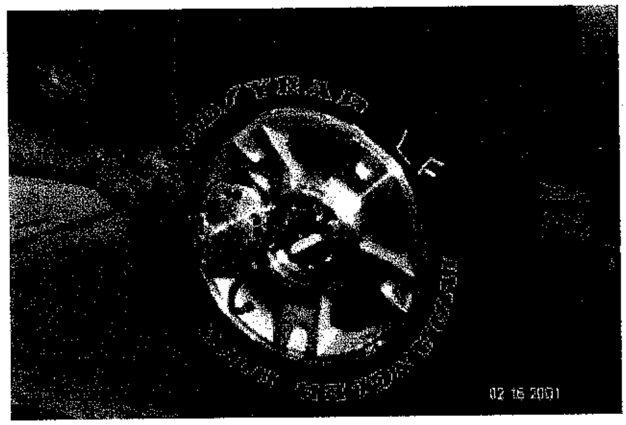


Figure 4 Cycloid's Sensor-Transmitter [2]

2.2.3 Fleet Specialties Co.

This system was also a prototype aftermarket pressure-sensor based TPMS. The sensor **(Figure 5)** replaced the cap on each valve stem. Each sensor **(Figure 6)** had its own digital identification code. This system had the capability to receive signals from up to 22 tyres simultaneously (it was adapted from a heavy truck application). The sensors' designated locations and cold inflation pressures were set at the factory. The sensors ordered for testing had a single warning threshold preset at 20 psi. This external mechanical-based sensor design did need to compensate its circuitry for temperature. The sensor and its battery could be installed and maintained without removing the tyre. Sensor location identifiers could be updated to adjust the warning threshold if needed. The receiving unit contained the antenna and the driver interface. The stated accuracy of the system was ±1.0 psi [2]. The system was designed to give a single "low tyre" warning. When tyre underinflation was detected, the sensor would send a warning signal every 3.5 seconds until the pressure level was corrected. The warning signal consisted of a "LOW TIRE" text message as well as illumination of one of the four tyres on the vehicle image display. There were no provisions to display tyre pressure or temperature values. The driver interface for the system is shown in **Figure 7** which is installed inside the car.

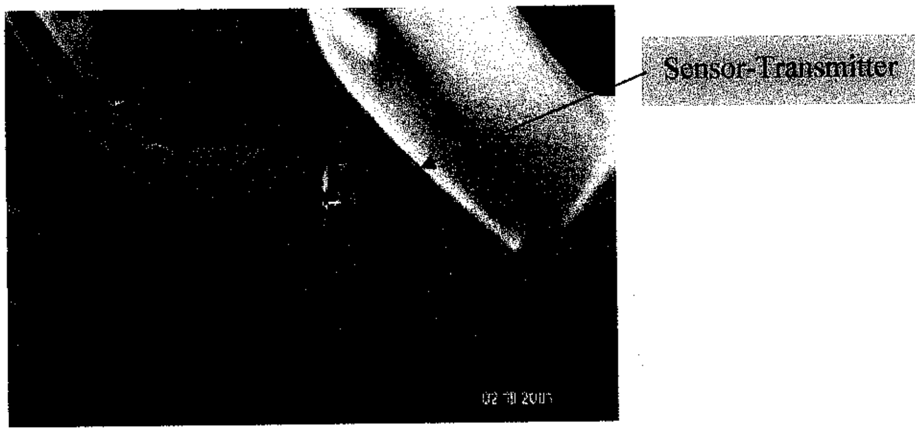


Figure 5 Location of sensor-Transmitter [2]

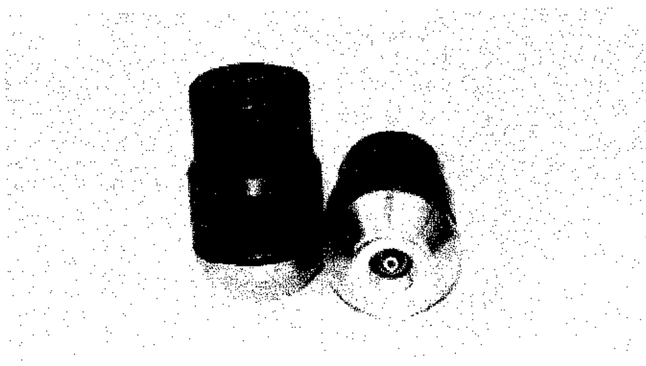


Figure 6 Fleet's sensor-Transmitter [2]

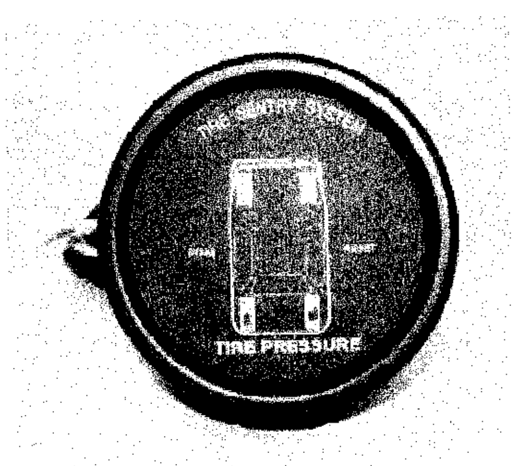


Figure 7 Fleet's Display [2]

2.2.4 Johnson Control Inc.

This system was an aftermarket pressure-sensor based TPMS. The pressure sensor/transmitter is displayed in **Figure 8**. The sensor was inserted inside each wheel rim, with the aluminum valve stem replacing the tyre valve stem. Each sensor had its own digital identification code. An antenna contained in the receiving unit was mounted in a battery powered replacement rear-view mirror. The stated accuracy of the system was 2 to 5 percent, depending on the operating temperature. Tyre pressure warning information was provided to drivers though a display that was integrated into the center rear-view mirror, as pictured in **Figure 9.** This system was designed to give two different levels of warning. The first was a "low pressure" warning, which occurred at 19.9 psi and consisted of a single auditory tone, or beep. The second was a "critically low pressure" warning, which occurred at 15.0 psi and consisted of a double beep [2]. In both cases, the display alternated between the word "LO" and the measured pressure of the lowest tyre. The tyre indicator light for each low tyre will also be illuminated. This system provided four different system status messages, each accompanied by a single beep. The first messages "OK" presented at the first press of the toggle button or the first movement of the vehicle after the system had been awakened from "sleep mode". The system presented a "no pressure alarm" displayed as "nP" once batteries were replaced until new pressure data was received. A low receiver battery alarm was provided when the system was activated and the batteries in the receiver were low, displayed as "BAT LO".

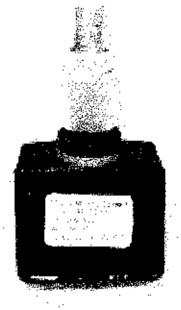


Figure 8 Johnson's Sensor-Transmitter [2]

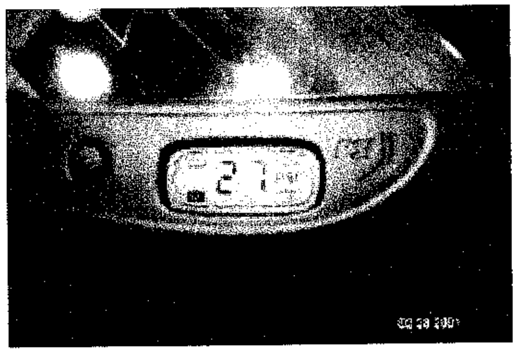


Figure 9 Rearview Mirror Display [2]

2.2.5 Pacific-Industries Co. LTD

The system was an aftermarket pressure and transmitter sensor based TPMS. The sensor was inserted inside each wheel rim, with the aluminum valve stem replacing the original tyre valve stem **(Figure 10).** Each sensor had its own digital identification code. One antenna was mounted in each wheel well, though one per axle may be sufficient depending on the size of the vehicle. The stated accuracy of the system was 1.8 psi. The driver interface for this system is shown in **Figure 11.** This system monitored both pressure and temperature and could provide warnings for these conditions for each of the four tyres individually. The system was designed to give four different levels of warnings. The first was a "below user target pressure" warning and auditory tone, which occurred when the pressure dropped below the level, set by the user. The pressure was sampled every 15 seconds. Normally, data was transmitted every 10 minutes; but, in the case of a warning condition, it was transmitted every 15 seconds. The second warning was a "below warning pressure" alert and audible signal, which occurred at 20.3 psi. The third warning was a "decreasing tyre pressure" warning that occurred when there was a loss of 2.9 psi in 15 seconds or a loss of 23.5 psi in 45 seconds. The fourth warning was the "temperature alarm" which activated when one of the tyres' contained air temperature of 230°F. The temperature or pressure could be checked at any time by the driver.

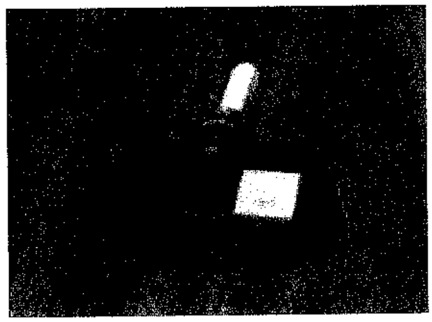


Figure 10 Pacific's Tyre Sensor-Transmitter [2]

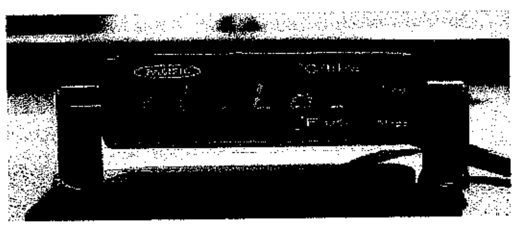


Figure 11 TPMS Display [2]

2.2.6 SmarTire Inc.

The system was an aftermarket pressure and transmitter sensor based TPMS. In this evaluation from the company, the "Full Function Display" was tested since it had the capability of displaying current tyre air pressure and temperature as well as temperature-compensated pressure levels and deviations from cold placard pressure [2]. This information could be shown for each tyre present on the vehicle individually. The sensor was fastened to the wheel with a metal band **(Figure 12).** Each sensor had its own digital identification code. The receiving unit contained the antenna and the display. The system monitored both pressure and temperature, which were sampled every 6 seconds. The internal tyre air temperature was used to calculate the equivalent cold inflation pressure. The stated accuracy of the system was 1.5 psi for pressure and 5.4° F for temperature. The system had the ability to monitor up to twenty tyres like heavy truck. The driver interface version tested in this program was the "Full Function Display", as shown in **Figure 13**. The system monitored each tyre on the vehicle individually and was designed to give three different warnings. The first was a "pressure deviation alert" warning and tone, which occurred when the pressure dropped below the level set by the user-defined [2]. The second warning was a "low pressure warning" and a pulsed tone, which occurred at a level, set by the user-defined [2]. The third warning was the "high temperature alert" which activated when one of the tyres reached a level set by user-defined [2]. The pressure deviation alert had optional temperature-compensated pressures, while the low pressure warning was fixed at a pressure level. The system allowed the driver to display the temperature, pressure, or deviation from placard of any tyre by scrolling through the display. Separate displays for the vehicle and a trailer were available. When power from the vehicle's battery is applied to the receiver, all icons present on the multi-function display are momentarily turned on, the warning light blinks once, and a warning beep is sounded [2]. The unit then goes blank. No data can be received until the vehicle is in motion. Once the vehicle is in motion, the system goes into stand-by mode (display shows vehicle outline and shaded rectangles representing tyres from which signals have been received).

Figure 12 System SmarTire Inc. In Tyre Sensor-transmitter fastened with metal band [2]

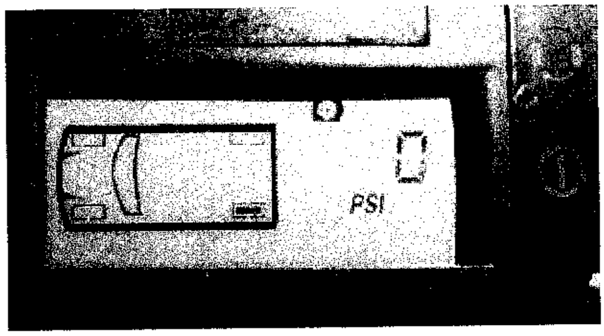


Figure 13 SmarTire Inc Full Function Display [2]

Conclusion on six Pressure-Based TPMS

Four of the six systems were tested in aftermarket system configurations due to a lack of original equipment systems [2]. The aftermarket system configurations means, the system that had been tested based on existing product in the market. Systems Fleet Specialties Co, Johnson Control Inc, Pacific-Industries Co. LTD were intended as add-on displays until vehicle manufacturers adopt the tyre monitoring systems as original equipment. System Beru is a good example of a pressure-sensor based system integrated into a vehicle as original equipment. This version was, however, the basic economy system and did not demonstrate the full functionality offered on other higher end models of this system. System cycloid was a very early prototype and used a laptop computer to simulate the display. This system was primarily intended to be an integrated original equipment system.

Within the next few years, the PSB systems are expected to retain essentially the same tyre pressure sensors but eliminate the add-on displays. The aftermarket receiver/display unit will be integrated into existing vehicle systems, lessening costs. The receiver portion of the display can be integrated into the vehicle's electronic control unit and perhaps interface though an existing key-less entry system.

CHAPTER 3
METHODOLOGY

3.1 Tyre Pressure Monitoring System (TPMS) Procedure

The TPMS consists of two primary components:

i. Sensor (inside the tyre)

This sensor is well place inside the tyre based on the research done by the author [2]. The pressure and temperature can be good measured inside the tyre.

ii. Receiver (inside car)

Since the receiver doesn't consist of any sensor, it can be placed inside the car. The reason to have the receiver inside the car is for the protection from any damage.

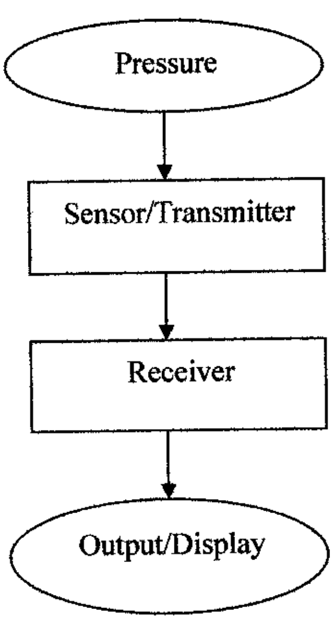


Figure 14 TPMS Basic Procedure

3.2 Designing Pressure Sensor

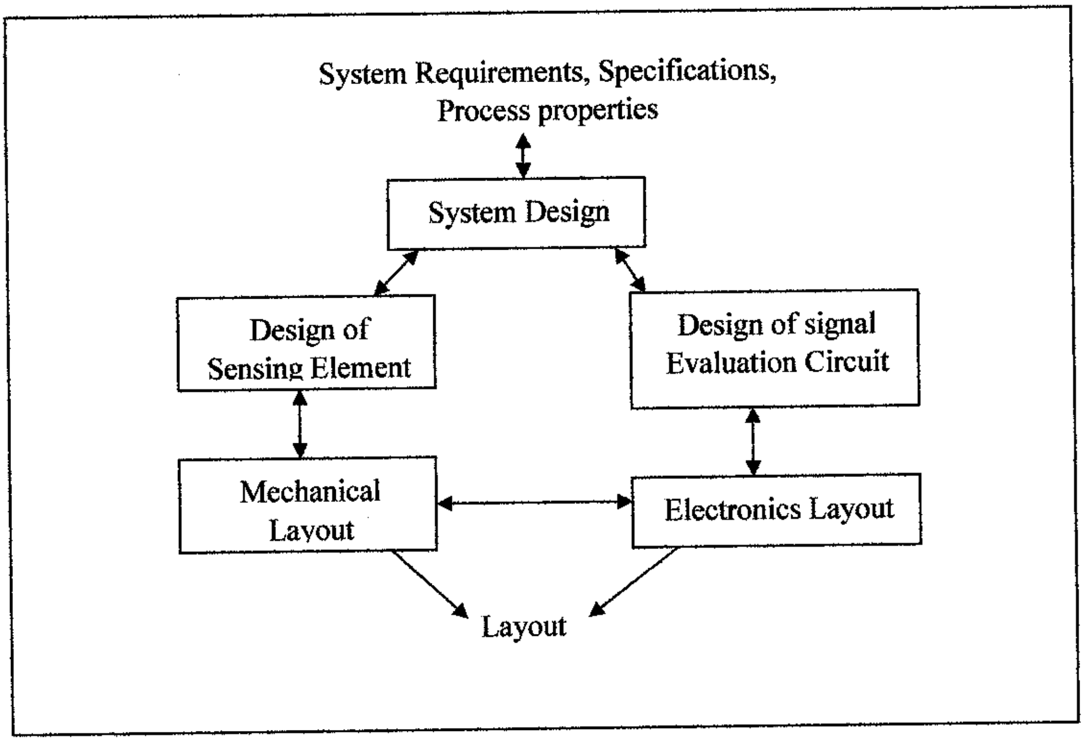


Figure 15 Work Flow in the development of MEMS sensors

The two basic approaches to organizing a design process are bottom-up and top-down. Very early in development, when people are still mainly doing research, most design procedure is bottom-up. But if the technologies being developed are getting more and more matured and people understand its capabilities and properties, the top-down approach is being used in developing products. The top-down approach is better suited to an industrial development process, where we usually start with the specifications required of the product.

A brief description of the work flow is outlined in **Figure 15.** Development work starts in a top-down style, with system requirement and specifications. The system design begins with analytical investigations of the system's behavior and performance and then uses methods and tools from system-level modeling and simulation. After finishing the system-level design, the system is partitioned into subsystems. After partitioning into subsystems, the micro machined and the electronic subsystems are designed.

The primary sensing element is a piezoelectric element constructed in such a way that when stressed by vibratory forces, a proportional electrical signal is produce. For the mechanical sensing element, three basic structural designs are used in manufacturing industrial. They are the flexural, compression and shear designs. All three designs contain the basic components of the piezoelectric element, seismic mass, base, and housing. In the flexural design the piezoelectric element is secured to the seismic mass in the form of a double cantilever beam. In the compression design; the crystal, quartz or ceramic, is sandwiched between the seismic mass and the base with an elastic pre-load bolt. Motion (vibration) into the base squeezes the crystal creating an output. The shear design subjects the sensing element to a shear stress.

Two types of integrated circuits are generally used in sensors: voltage and charge amplifiers. Low capacitance quartz sensing elements exhibit a very high voltage output (according to $V = q/C$) and are typically used with MOSFET voltage amplifiers [3]. Ceramic sensing elements which exhibit a very high charge output are normally coupled to charge amplifiers. The gain of the amplifier then determines the sensor sensitivity.

Finally the last stage of typical designing pressure sensor is the layout of the micromechanical and electronic parts of the system.

3.3 Tools and Equipment

When determining the need for the implementation of a project especially a tyre pressure monitoring system, there are many important factors to consider. The following are the basic components that involved in this project:

i. Pressure sensor

   The main purpose of this project is to develop a step by step approach on developing miniature or MEMs pressure sensor.

ii. PIC microcontroller

   The main element in TPMS, brain of the project is microcontroller unit. RfPIC is frequently use in most research.

iii. Transmitter elements

The transmitter to be used is integrated RfPIC.

iv. Receiver elements.

RLP-434 receiver with frequency 433.92MHz will be used.

v. CoventorWare Software

CoventorWare is the most comprehensive suite of MEMS design tools in the industry. It acts as a seamless integrated design environment that reduces design risk, speeds time-to-market and lowers development costs. The CoventorWare methodology enables schematic-based behavioral modeling and detailed 3-D multi-physics numerical analysis to support virtually every MEMS application, such as automotive sensors.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Findings

The author has found 2 existing project and related circuit that is very useful in the completion of TPMS project. This finding might helpful to produce the real working applications.

4.1.1 Intersema TPMS [4]

Intersema is the company that involved in TPMS. The Tyre Pressure Measurement Module (TPMM) consists of the following main blocks:

- RfPIC12F675 Microcontroller with integrated 434 MHz RF transmitter for data transmission and 10bit AD converter for pressure & temperature measurements, 6 I/O pins for system control.
- Simple interface electronic for interfacing the pressure sensor to the AD converter (LMV341 operational amplifier)
- Low frequency link (LF-link) for calibration and setup commands (inductance and transistor)

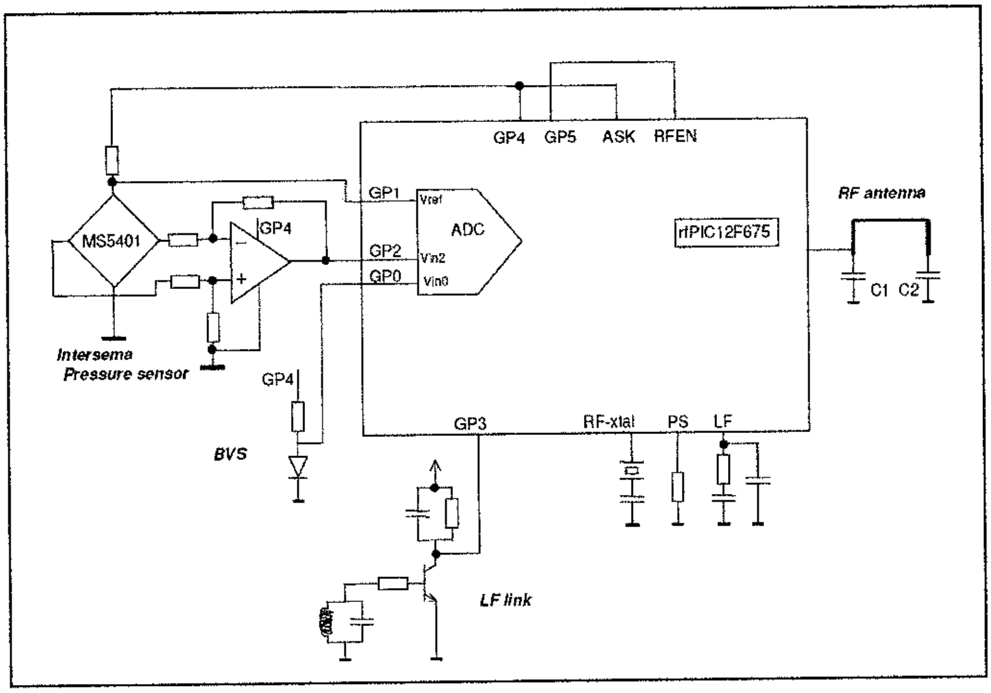


Figure 16 Schematic on simple connection between Pressure sensor and RfPIC [4]

Pressure/Temperature measurement

For this existing circuit, the temperature measurement is not much helpful since it's out of author objective, but for the future work it will be worthy. Both pressure and temperature values can directly be measured on the pressure sensor bridge (MS5401):

- for the pressure measurement, the differential output voltage from the pressure sensor is converted pre-amplified and converted
- for the temperature measurement, the sensor bridge resistor is sensed through a resistor and converted

In order to reduce power consumption, the sensor will only be switched on for a very short time. When not measuring, all IO ports are at low output, which shut down the sensor and the pre-amplifier.

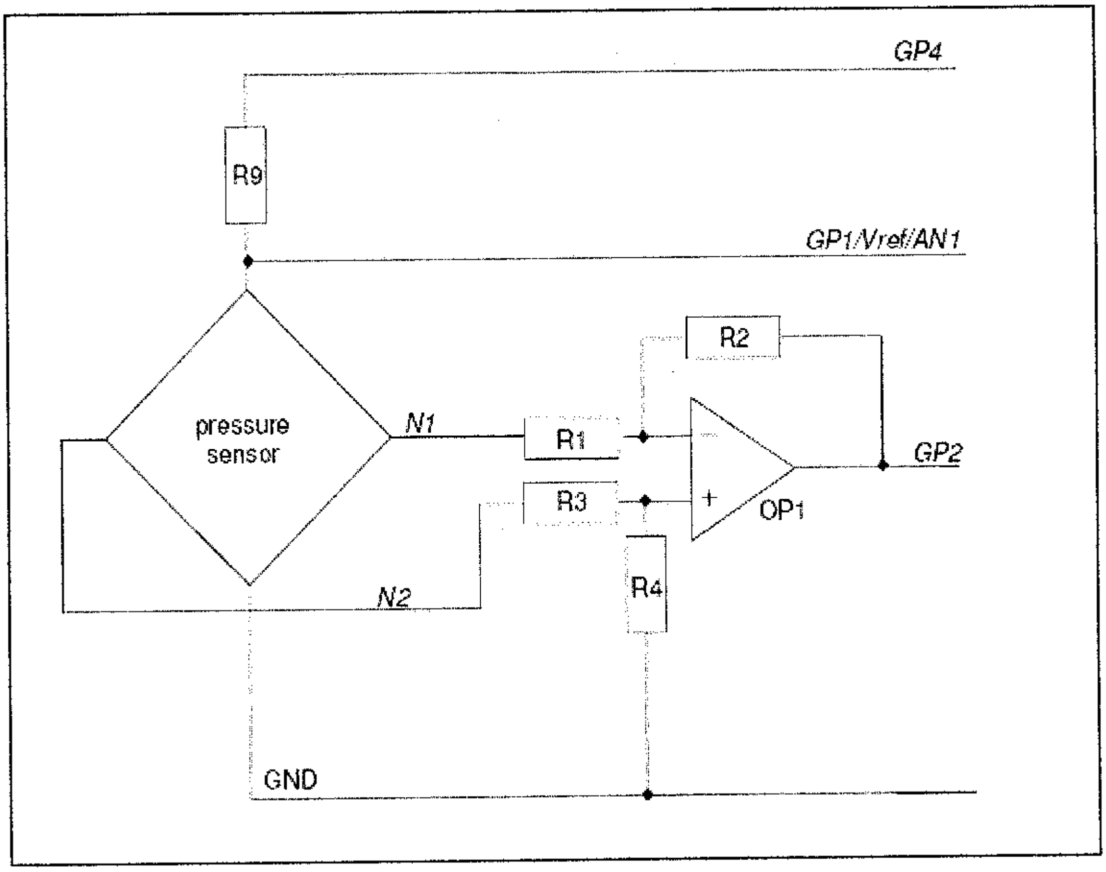


Figure 17 Schematic of simple sensor interface circuit. [4]

During pressure measurement the I/O pins of the microcontroller are in following states:

- GP1 output pin pulls the bridge directly to *Vdd.* GP1 is also used as the reference for the ADC conversion. This way the internal port resistance in the microcontroller has so no influence on the ADC result, even if it does not pull the bridge exactly to *Vdd.*

- GP2 is used to measure the differential pressure voltage through the preamplifier with the AD converter. The gain of the preamplifier is chosen to have maximal resolution, and ensuring that the signal will not saturate with sensor process variation, pressure and temperature variations.

- GP4 serves as output to pull up the temperature measurement resistor to avoid current flowing through R9, which is not used for pressure measurements. GP4 is also used to enable the LMV341 operational amplifier.

During temperature measurement (future work) the IO pins of the microcontroller are in following states:

- GP4 pulls up the sensor over the serial resistor R9. The pressure sensor bridge and R9 form a resistive divider, which is temperature dependent, since the pressure sensor resistors have a quite large temperature coefficient (3000 ppm/°C).
- GP1 serves as analog input of the AD converter. This time, *Vdd* serves as *Vref*. The parasitic serial resistance (output resistance of the port) is not cancelled and care has to be taken for the parasitic resistance of the port, which is about 200 Ohm. For this reason, the serial resistor R9 has to be chosen quite large (about 10k), to minimize the influence of the parasitic port resistance.

RF Transmitter

The RfPic allows two modulations: ASK (amplitude modulation) or FSK (frequency modulation). The ASK modulation is used in this design, but FSK modulation could be used too [4].

For best transmission efficiency, the antenna's resonance frequency has to be at transmission frequency (434MHz), and its impedance has to match the output impedance of the transmitter inside the RfPIC (about 300 Ohm at 434MHz) [3]. To watch these components, two capacitors are placed in the loop of the antenna:

- C1 (transmitter output to ground): this capacitor strongly affects the impedance of the antenna. For the actual antenna design, it is about 19 pF.
- C2 (antenna output to gnd): this capacitor determines the resonance frequency of the antenna together with the inductance and the resistance of the antenna itself. For actual antenna design it is about 4pF.

To avoid trimming of the capacitors during production, the quality factor of the antenna can be reduced. Quality factor (Q) of a reactive component is the ratio of energy stored and then returned by a capacitor to the energy dissipated in the resistance [6]. Of course effective transmission power will be reduced and usable range will be shorter. To decrease the Q (quality factor) of the antenna, a resistor can be placed between the transmitter output and Vdd. Decreasing this resistance reduces the Q. The inductance from transmitter output to Vdd is for DC polarisation of the antenna.

LF-Link

The LF link is used as receiver of the TPMM. Since the TPMM can be in sleep mode during data arrival, the LF link must be able to wake up the processor without adding current consumption during sleep mode.

Simplest way would be to use the internal comparator of the microcontroller. Unfortunately the reference resistor string of that comparator does take too much power (Vdd/48 kOhm = 62.5 uA @ 3.0 V) to keep it on all the time and so the comparator cannot be used.

The LC tank must so be able to generate a quite high voltage (>> Vdd/2), so that the controller can be waked up from the sleep mode through a simple interrupt on GP3 pin.

An ideal operating frequency is somewhere between 10 kHz to 200 kHz, perhaps a bit higher frequency is better suited for a faster transmission (shorter on time saves power.

4.1.2 Microchip TPMS

The TPMS system consists of the following major component:

i. Sensor/Transmitter Device

ii. RF Receiver Module

iii. Low Frequency (LF) Commander device

iv. Control unit

v. Pressure vessel (Tyre)

Theory of operation

The S/TX device comprises two integrated circuits:

- Microchip's rfPIC12F675 MCU/RF transmitter IC
- Sensonor SP-13 (pressure, temperature and low-voltage sensor IC)

In addition, the S/TX also includes LF input circuitry. This circuitry allows the S/TX device to receive special commands via the LF link. Refer to **Appendix B** for additional circuit detail.

Receiver Module

A central RF receiver module receives transmissions from the individual S/TX devices. The receiver can also be used as a remote keyless entry receiver, saving on overall system cost. The design of the RF receiver module falls beyond the intent of this document. A functional RF receiver module is assumed.

LF Commander Device

The LF commander is designed to send specific commands to the S/TX unit via a 125 kHz ASK modulated signal. The LF link communicates over a short distance (1 meter or less), thus making it capable of communicating with the wheel in its immediate range. LF magnetic communications is well suited for sending commands to the S/TX devices. These commands, when received by the S/TX device, instruct it to carry out specific tasks

Control Unit

The control unit is responsible for initiating communications, interpreting received data and reporting the relevant information back to the vehicle. The unit will only be treated from a system overview perspective.

Pressure Vessel

The pressure vessels (tyres) are the measurement component, with pressure and temperature values measured and reported.

behavior. INTEGRATOR bridges this communication gap by enabling MEMS designers to extract reduced order macro models that can be easily incorporated into IC simulations (Figure 19). INTEGRATOR will certainly save time and may eliminate needless fabrication cycles.

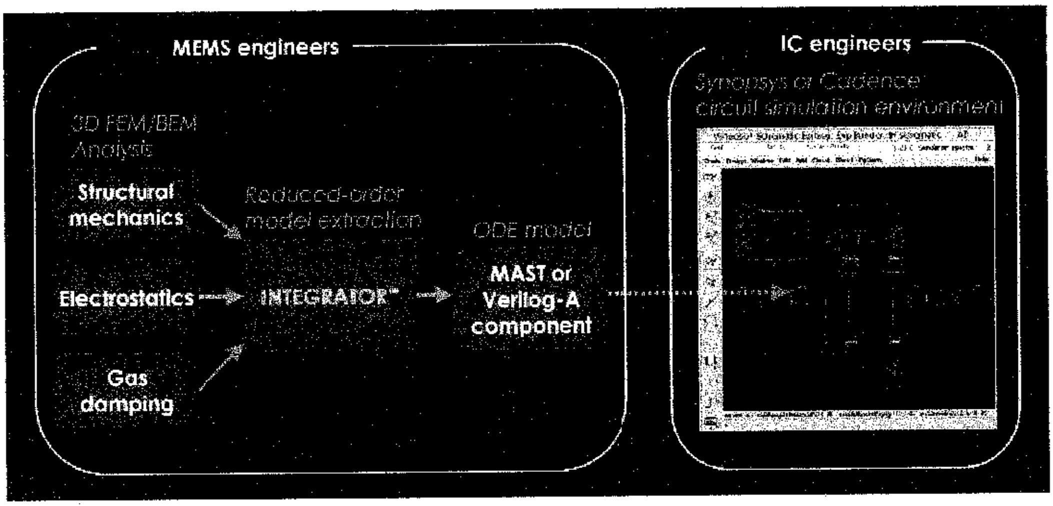


Figure 19 INTEGRATOR bridges the gap between MEMS and IC designer [7]

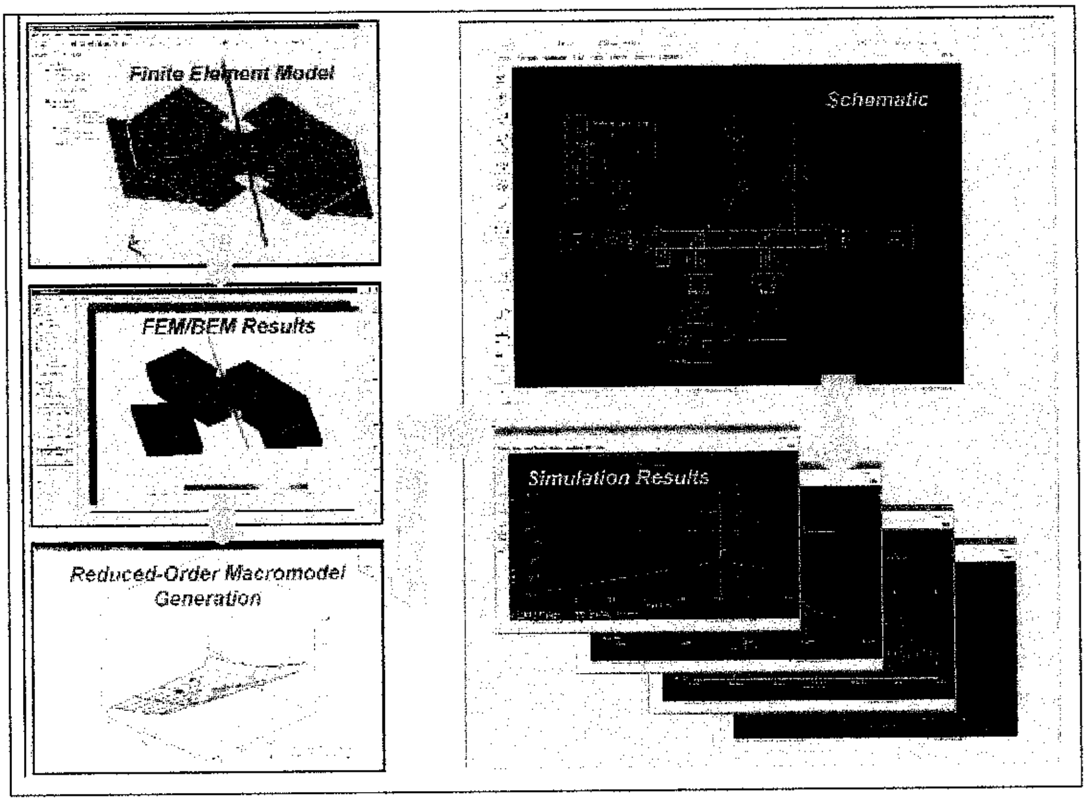


Figure 20 INTEGRATOR automatically loads the user defined macro model parameters into Cadence [7]

4.2.2 MEMS Technology Pressure Sensors

Research into solid state pressure sensor began as far back as the 1960s [8]. Since then there have been many developments both in micromachining and sensing techniques, which have enabled MEMS pressure sensor to mature into a commercially successful solution for many sensing application like in TPMS. The first silicon pressure sensors were based on a piezoresistive read out mechanism. At the moment, piezoresistive pressure sensors are still the most widely used. Capacitive read out mechanism are inherently less sensitive to temperature variations and extremely low power consumptions can be obtained.

Piezoresistive Pressure Sensors

As mentioned above, most currently available silicon pressure sensors use a piezoresistive read out mechanism. **Figure 21** shows a typical example of a bulk micromachined piezoresistive pressure sensor. The resistor may be diffused in the membrane or deposited on the membrane with an immediate isolation layer (SiO_2). Usually the resistors are connected in a Wheatstone bridge configuration for temperature compensation.

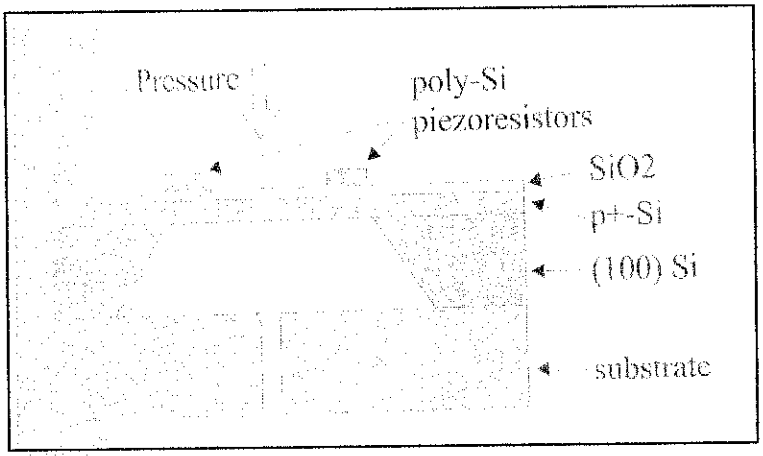


Figure 21 Schematics cross section of a typical bulk micromachined piezoresistive pressure sensor [8].

A Wheatstone bridge is a network of four resistive legs. One or more of these legs can be active sensing elements. **Figure 22** shows a Wheatstone bridge circuit diagram.

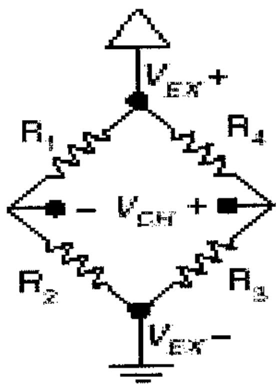


Figure 22 Basic Wheatstone Bridge Circuit Diagram [9].

The Wheatstone bridge is the electrical equivalent of two parallel voltage divider circuits. R_1 and R_2 compose one voltage divider circuit, and R_4 and R_3 compose the second voltage divider circuit. The output of a Wheatstone bridge is measured between the middle nodes of the two voltage dividers.

A physical phenomenon, such as a change in strain applied to a specimen or a temperature shift, changes the resistance of the sensing elements in the Wheatstone bridge. The Wheatstone bridge configuration is used to help measure the small variations in resistance that the sensing elements produce corresponding to a physical change in the specimen.

The main advantages of a piezoresistive read out mechanism are the simple fabrication process, the high linearity and the fact that the output signal is conveniently available as a voltage. The main problems are the large temperature sensitivity and drift. Furthermore, because of the low sensitivity of piezoresistors, piezoresistive devices are not suitable for accurate measurement of very low pressure differences.

Capacitive Pressure Sensors

As mentioned before, capacitive pressure sensors have several advantages compared to piezoresistive sensors. Especially at low pressure differences capacitive sensors offer a significant advantage because of their much higher sensitivity. Furthermore, capacitive pressure sensor are inherently less sensitive to temperature variations and offer a much more better long term stability. On the other hand, capacitive pressure sensor are inherently non linear and the measurement of small capacitance changes requires much more complicated electronic interface circuits than piezoresistive sensors.

Capacitive pressure sensors are typically based upon a parallel plate arrangement whereby one electrode is fixed and the other flexible. As the flexible electrode deflects under applied pressure, the gap between electrodes decreases and the capacitances increases. As early device, shown in **Figure 23**, consists of an anistropically etched silicon diaphragm with the fixed electrode being provided by a metallized Pyrex 7740 glass die [8]. The glass and silicon die were joined using anodic bonding at die level. This device demonstrated the main attractions of capacitive sensing, these being high sensitivity to pressure, low power consumption, and low temperature cross sensitivity.

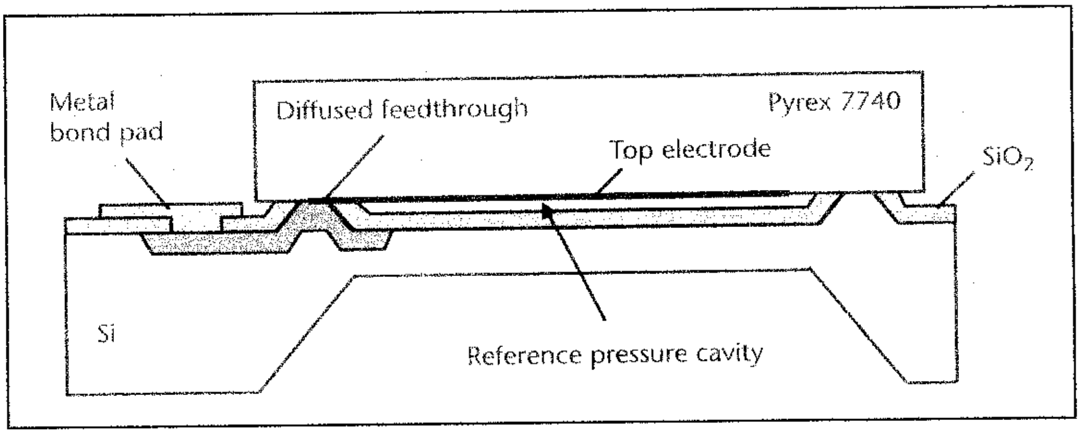


Figure 23 Early silicon/Pyrex capacitive pressure sensor [10].

4.2.3 Material for Sensors

Material suitable for transduction elements in sensors ideally should have the following properties:

i. High piezorelectric sensitivity
ii. High mechanical strength
iii. High rigidity (high modulus of elasticity)
iv. High electric insulation resistance
v. Linear relationship between mechanical stress and electric polarization
vi. High stability of all properties
vii. Low temperature dependence of all properties within a wide temperature range
viii. Low production cost

Quartz

Quartz is still the most important single crystal serving as transduction element in piezoelectric sensors. Its chemical formula SiO_2 and it is found in several modifications, constituted of oxygen tetrahedrons with silicon at the center position. Quartz has a density of $2{,}649.10^3$ kg/m and a hardness of 7 on the Mohs' scale [11]. It is practically insoluble in water and resistant against most acids and alkali. Quartz melts at 1710°C [11]

Tourmaline

Tourmaline is from the chemical point of view, an aluminum-borosilicate. Its relatively complex composition can be described by the formula (Na, Ca) $(Mg, Fe)_3$ $B_3Al_6Si_6(O, OH,F)_{31}$[11]. Tourmaline has a high mechanical strength and, like quartz, is resistant against most acids and alkali. Tourmaline offers the advantage that it can not twin and does not have a phase change below 900°C which makes possible to use it in sensors for a very wide temperature range up to about 700°C. Its biggest disadvantages are the inherent strong pyroelectric effect and the problem of finding crystals of acceptable quality and sufficient quantity from natural occurrences.

4.3 Development of LCD display unit

Simulation and Design Process for TPMS

Besides doing research on pressure sensor, the author takes the opportunity to produce prototype for TPMS. The author had done a simulation using PIC simulator IDE. From interface of the PIC simulator IDE **(Figure 24)**, the author set the directory of file location to the program and selects type of microcontroller and clock frequency. The objective of the simulation is to display output on LCD display using analog input **(Figure 25)**. Since the circuit receives analog input from the sensors, PIC16F877 was chosen as it have build-in A/D converter. Below are the procedures on the simulation process:

1. File lcd.bas was examined from the application folder. This program reads analog value on AN0 analog input and displays formatted output on the attached 2x16 LCD module. File lcd.asm was generated using integrated Basic compiler. File lcd.hex was generated using integrated assembler.
2. Start PIC Simulator IDE.
3. Click on Options\Select Microcontroller.
4. Select 'PIC16F877' and click on Select button.
5. Click on File\Load Program.
6. Select lcd.hex file and click on Open. That will load the program into PIC program memory
7. Click on Tools\Microcontroller View. That will open the Microcontroller View window **(Figure 26)**.
8. Click on Tools\LCD Module. That will open the LCD Module simulator window
9. Reposition the windows on the screen to get better view.
10. Click on Setup button on LCD Module window.
11. Click on 'Data Lines' field and set it to PORTB.

12. Click on 'Interface' field and set it to 8-bit.

13. Click on 'RS Line' field and set it to PORTD, 1.

14. Click on 'E Line' field and set it to PORTD,3

15. Click on 'R/W Line' field and set it to PORTD,2

16. Click on 'Apply!' to close LCD interface setup dialog.

17. Select the Rate\Extremely Fast simulation rate.

18. Click on Simulation\Start. The simulation will start immediately.

19. Click on A button associated with RA0/AN0 pin.

20. Using the slider change the analog value on this pin and click on accept button

21. Watch how this change affects the LCD Module.

22. The last three steps can be repeated.

23. The simulation can be stopped any time by clicking on Simulation\Stop.

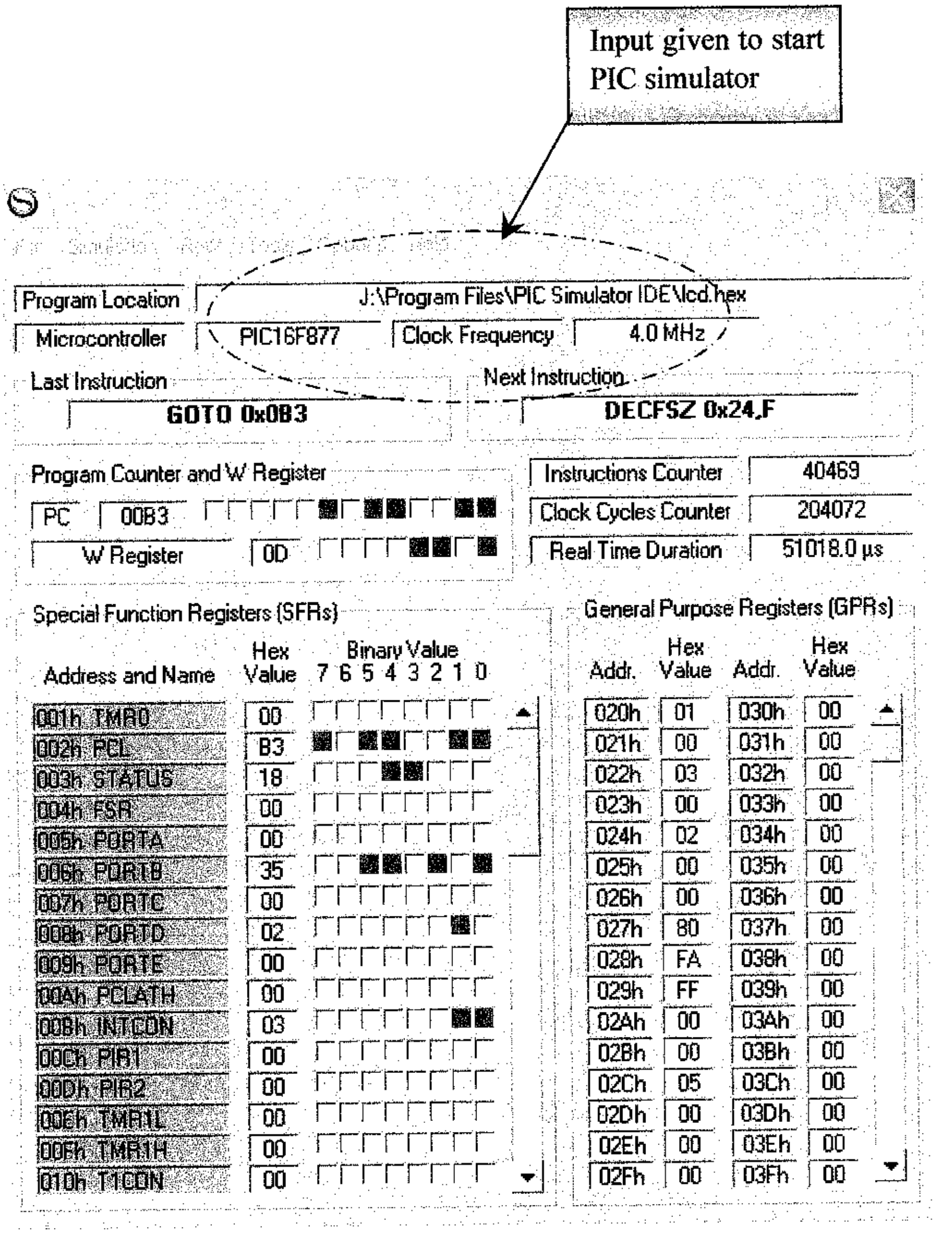


Figure 24 PIC Simulator IDE

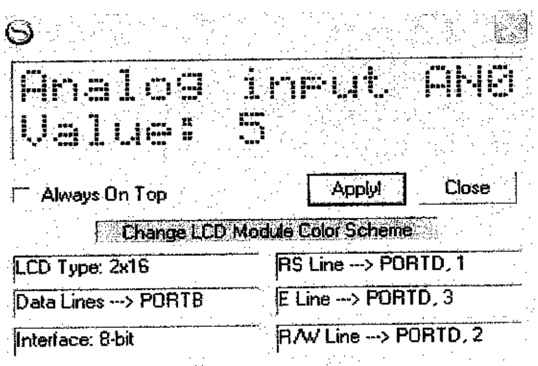


Figure 25 LCD Module Display

From **Figure 25**, the screenshot shows the output of the system. LCD type using here is 2x16 with 8 bit interface. All PORTB was set to data lines; PORTD, 1 set to RS line; PORTD, 3 set to E Line; and PORTD, 2 set to r/w Line.

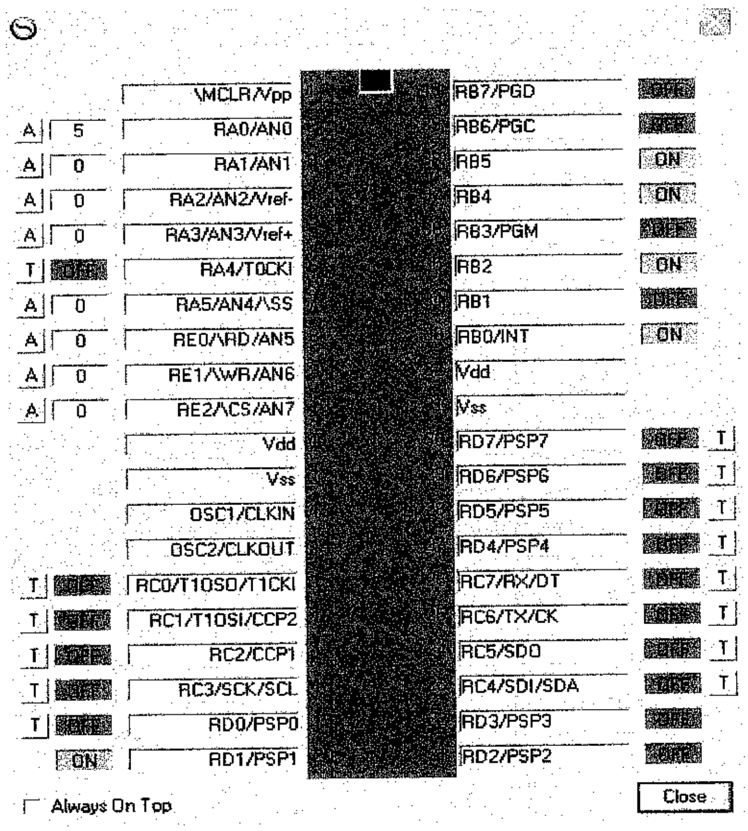


Figure 26 PIC16F877 Microcontroller View.

Figure 26 show the view of microcontroller while the programming is running. The input is given through RA0/AN0 which is 5. The 'ON' display the output is activated.

From the simulation, the author just assumes an analog input which comes from the sensor is 5V analog. The Basic compiler file and assembly file was attached on the **Appendix C.**

Although the simulation on displaying LCD is successful, the next step on these activities is not continued due to some problem. Here are the problems encountered in this activity:

i. Separation using PIC16F877 with transmitter module isn't compatible to this project. The real application is using RfPIC which PIC with integrated transmitter.

ii. The unavailability MEMS pressure sensor in the market since it's very costly and over the FYP budget.

iii. Many aspect need to cover overall this project (eg: pressure sensor, transmitting data, receiving elements, and displaying properly inside car) which was required at least 3 people to handle.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Relevancy to the Objectives

Overall, the principal objective of this report is to provide an overview on how the research of the final year project was conducted throughout the beginning of this semester. It serves as a framework, will enhance student skills in the process of applying knowledge, expanding thoughts, solving problems independently and presenting findings through minimum guidance and supervision.

For the conclusion tyre pressure monitoring system using a pressure sensor is still a new concept in terms of safety procedure in vehicle. Only the car from United State Company had launched these systems to their product. The United States government has passed legislation that will eventually require all new passenger vehicles to be equipped with tyre pressure monitoring systems. The challenge in this project is to produce a similar or better design using microelectronic devices. Hopefully these systems can be implemented in local automotive company such as Proton and Perodua.

Looking from the economic perspective, this project is definitely very costly. The license for the CoventorWare is cost about RM 4 million. The pressure sensor also priced around thousand dollars.

5.2 Recommendation

As to end of presentation, it is therefore important to suggest some improvements and recommendations for the benefit of the project. In any cases at all, engineers are known to impressive and modify to better the system. As mentioned earlier in discussion, this project can be adapted to suit different applications.

Therefore the recommendations suggested are as follows:

- Design the real applications on the MEMS pressure sensor based on initial research.
- Fabricate the sensor based on the design method.
- With permissible pressure sensor, come up with a working prototype of TPMS
- The overall project needs to have at least 3 students to complete the entire task since the workload is very high.
- Hopefully the university could locate some budget for such interesting topic like TPMS to make it real happened.

All these recommendations will definitely improve the quality and can be presented well to public.

REFERENCES

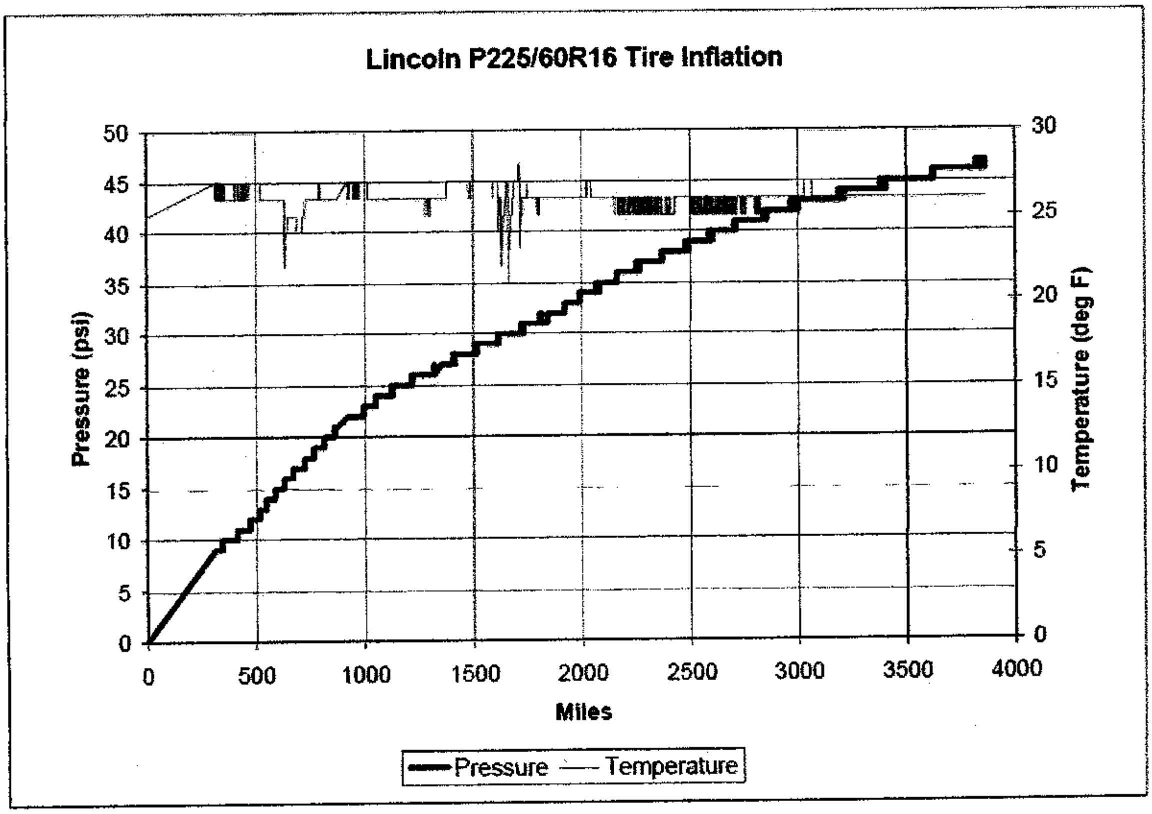
1. SG2011, REV 1, 12/2/2004 web based on www.freescale.com
2. "An evaluation of Existing Tire Pressure Monitoring Systems" DOT HS 809 297, National Highway Traffic Safety Administration, July 2001.
3. PCB Piezotronic web based on http://www.pcb.com/techsupport/tech_signal.php
4. AN601, Intersema Tyre Pressure Monitoring web based on http://www.intersema.ch.
5. "Tire Pressure Monitoring (TPM) System (AN238)" Ruan Lourens, Microchip Technology Inc.
6. J Marek, "Sensor for Automotive Technology" Wiley-VCH, 2003.
7. INTEGRATOR Coventor web based on http://www.coventor.com
8. M.Elwenspek, "Mechanical Microsensors", Springer, 2001
9. National Instrument web based http://zone.ni.com/devzone/conceptd.nsf/
10. Stephen Beeby, "MEMS Mechanical Sensors" Artech House, Inc,
11. 2004G.Gautschi, "Piezoelectric Sensorics" Springer, 2002.

APPENDICES

APPENDIX A

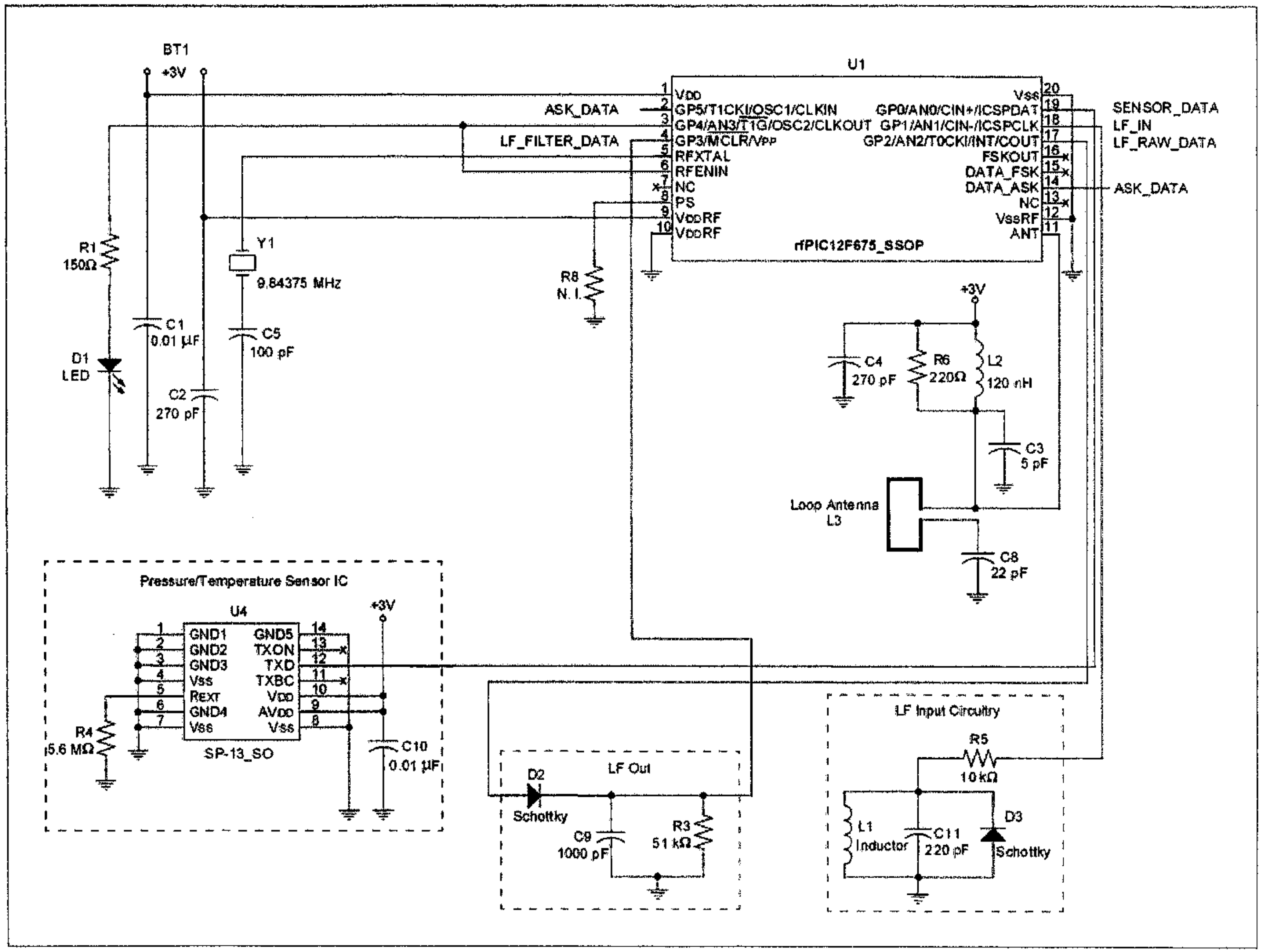
CYCLOID AUTOPUMP EXAMPLE TYRE INFLATION CURVE

For normally inflated tires, the Cycloid AutoPump's inertial driven compressor adds a maximum of 2 psi per hour of driving. The inflation rate of the pump is high at low pressures and drops off as tire pressure increases. The pump will eventually reach its preset equilibrium level with the tires and will not be able to add more pressure. The inflation system is currently configured to handle cold inflation pressures up to 45 psi; though the pump has the theoretical capacity of 65 psi.



APPENDIX B

TPM SENSOR/TRANSMITTER SCHEMATIC


BT1
+3V
R1
150Ω
D1
LED
C1
0.01 µF
C2
270 pF
Y1
9.84375 MHz
C5
100 pF
ASK_DATA
LF_FILTER_DATA
R8
N. I.
U1
VDD
GP5/T1CKI/OSC1/CLKIN
GP4/AN3/T1G/OSC2/CLKOUT
GP3/MCLR/VPP
RFXTAL
RFENIN
NC
PS
VDDRF
VDDRF
Vss
GP0/AN0/CIN+/ICSPDAT
GP1/AN1/CIN-/ICSPCLK
GP2/AN2/T0CKI/INT/COUT
FSKOUT
DATA_FSK
DATA_ASK
NC
VssRF
ANT
rfPIC12F675_SSOP
SENSOR_DATA
LF_IN
LF_RAW_DATA
ASK_DATA
+3V
C4
270 pF
R6
220Ω
L2
120 nH
C3
5 pF
Loop Antenna
L3
C8
22 pF
Pressure/Temperature Sensor IC
U4
GND1
GND2
GND3
Vss
REXT
GND4
Vss
GND5
TXON
TXD
TXBC
VDD
AVDD
Vss
SP-13_SO
R4
5.6 MΩ
+3V
C10
0.01 µF
LF Out
D2
Schottky
C9
1000 pF
R3
51 kΩ
LF Input Circuitry
R5
10 kΩ
L1
Inductor
C11
220 pF
D3
Schottky

APPENDIX C

16F877 SOURCE CODE

Basic Compiler - lcd.bas

```
Define ADC_CLOCK = 3
'defaultvalue is 3

Define ADC_SAMPLEUS = 10
'default value is 20

Define LCD_BITS = 8 'allowed
values are 4 and 8 - the number
of data interface lines

Define LCD_DREG = PORTB

Define LCD_DBIT = 0 '0 or 4 for
4-bit interface, ignored for 8-
bit interface

Define LCD_RSREG = PORTD

Define LCD_RSBIT = 1

Define LCD_EREG = PORTD

Define LCD_EBIT = 3

Define LCD_RWREG = PORTD 'set to
0 if not used, 0 is default

Define LCD_RWBIT = 2 'set to 0
if not used, 0 is default

Define LCD_COMMANDUS = 100
'delay after LCDCMDOUT, default
value is 5000

Define LCD_DATAUS = 10 'delay
after LCDOUT, default value is
50

Define LCD_INITMS = 1 'delayused
by LCDINIT, default value is 100

'the last three Define
directives set the values
suitable for simulation; they
should be omitted for a real
device


Dim an0 As Word


TRISA = 0xff 'set all PORTA pins
as inputs

ADCON1 = 0 'set all PORTA pins
as analog inputs

Lcdinit 'initialize LCD module;
cursor is off

loop:

      Adcin 0, an0

      Lcdcmdout LcdClear 'clear
LCD display

      Lcdout "Analog input AN0"
'text for the line 1

      Lcdcmdout LcdLine2Home
'set cursor at the beginning of
line 2


      Lcdout "Value: ", #an0
'formatted text for line 2

      WaitMs 1 'larger value
should be used in real device

Goto loop 'loop forever
```

Assembler - lcd.asm

```
; Begin
        R0L EQU 0x20
        R0H EQU 0x21
        R1L EQU 0x22
        R1H EQU 0x23
        R2L EQU 0x24
        R2H EQU 0x25
        R3L EQU 0x26
        R3H EQU 0x27
        R4L EQU 0x28
        R4H EQU 0x29
        R5L EQU 0x2A
        R5H EQU 0x2B
        ORG 0x0000
        BCF PCLATH,3
        BCF PCLATH,4
        GOTO L0002
        ORG 0x0004
        RETFIE
L0002:      NOP
; 1: Define ADC_CLOCK = 3
'default value is 3
; 2: Define ADC_SAMPLEUS = 10
'default value is 20
; 3: Define LCD_BITS = 8
'allowed values are 4 and 8 -
the number of data interface
lines
; 4: Define LCD_DREG = PORTB
; 5: Define LCD_DBIT = 0 '0 or 4
for 4-bit interface, ignored for
8-bit interface
; 6: Define LCD_RSREG = PORTD
; 7: Define LCD_RSBIT = 1
; 8: Define LCD_EREG = PORTD
; 9: Define LCD_EBIT = 3
; 10: Define LCD_RWREG = PORTD
'set to 0 if not used, 0 is
default
; 11: Define LCD_RWBIT = 2 'set
to 0 if not used, 0 is default
; 12: Define LCD_COMMANDUS = 100
'delay after LCDCMDOUT, default
value is 5000
; 13: Define LCD_DATAUS = 10
'delay after LCDOUT, default
value is 50
; 14: Define LCD_INITMS = 1
'delay used by LCDINIT, default
value is 100
; 15: 'the last three Define
directives set the values
suitable for simulation; they
should be omitted for a real
device
; 16:
; 17: Dim an0 As Word
;       The address of 'an0' is
0x2C
; 18:
; 19: TRISA = 0xff 'set all
PORTA pins as inputs
        BSF STATUS,RP0
        MOVLW 0xFF
        MOVWF 0x05
        BCF STATUS,RP0
; 20: ADCON1 = 0 'set all PORTA
pins as analog inputs
        BSF STATUS,RP0
        CLRF 0x1F
        BCF STATUS,RP0
; 21: Lcdinit 'initialize LCD
module; cursor is off
        BCF 0x08,3
```

```
        BCF 0x08,1
        BCF 0x08,2
        BSF STATUS,RP0
        BCF 0x08,3
        BCF 0x08,1
        BCF 0x08,2
        CLRF 0x06
        BCF STATUS,RP0
        MOVLW 0x01
        MOVWF R0L
        MOVLW 0x00
        MOVWF R0H
        CALL W001
        MOVLW 0x33
        CALL LC02
        MOVLW 0x33
        CALL LC02
        MOVLW 0x33
        CALL LC02
        MOVLW 0x38
        CALL LC02
        MOVLW 0x0C
        CALL LC02
        MOVLW 0x01
        CALL LC02
; 22:
; 23: loop:
L0001:      NOP
; 24: Adcin 0, an0
        BSF STATUS,RP0
        BSF ADCON1,7
        MOVLW 0x00
        BCF STATUS,RP0
        MOVWF R0L
        CALL A001
        BSF STATUS,RP0
        MOVF ADRESL,W
        BCF STATUS,RP0
        MOVWF 0x2C
        MOVF ADRESH,W
        MOVWF 0x2D
; 25: Lcdcmdout LcdClear 'clear
LCD display
        MOVLW 0x01
        CALL LC02
; 26: Lcdout "Analog input AN0"
'text for the line 1
        MOVLW 0x41
        CALL LC01
        MOVLW 0x6E
        CALL LC01
        MOVLW 0x61
        CALL LC01
        MOVLW 0x6C
        CALL LC01
        MOVLW 0x6F
        CALL LC01
        MOVLW 0x67
        CALL LC01
        MOVLW 0x20
        CALL LC01
        MOVLW 0x69
        CALL LC01
        MOVLW 0x6E
        CALL LC01
        MOVLW 0x70
        CALL LC01
        MOVLW 0x75
        CALL LC01
        MOVLW 0x74
        CALL LC01
        MOVLW 0x20
        CALL LC01
        MOVLW 0x41
        CALL LC01
```

```
        MOVLW 0x4E
        CALL LC01
        MOVLW 0x30
        CALL LC01
; 27: Lcdcmdout LcdLine2Home
'set cursor at the beginning of
line 2
        MOVLW 0xC0
        CALL LC02
; 28: Lcdout "Value: ", #an0
'formatted text for line 2
        MOVLW 0x56
        CALL LC01
        MOVLW 0x61
        CALL LC01
        MOVLW 0x6C
        CALL LC01
        MOVLW 0x75
        CALL LC01
        MOVLW 0x65
        CALL LC01
        MOVLW 0x3A
        CALL LC01
        MOVLW 0x20
        CALL LC01
        MOVF 0x2C,W
        MOVWF R2L
        MOVF 0x2D,W
        MOVWF R2H
        CALL LC21
; 29: WaitMs 1 'larger value
should be used in real device
        MOVLW 0x01
        MOVWF R0L
        MOVLW 0x00
        MOVWF R0H
        CALL W001
; 30: Goto loop 'loop forever
        GOTO L0001
; End of program
L0003:      GOTO L0003
; Division Routine
D001:  MOVLW 0x10
       MOVWF R3L
       CLRF R2H
       CLRF R2L
D002:  RLF R0H,W
       RLF R2L,F
       RLF R2H,F
       MOVF R1L,W
       SUBWF R2L,F
       MOVF R1H,W
       BTFSS STATUS,C
       INCFSZ R1H,W
       SUBWF R2H,F
       BTFSC STATUS,C
       GOTO D003
       MOVF R1L,W
       ADDWF R2L,F
       MOVF R1H,W
       BTFSC STATUS,C
       INCFSZ R1H,W
       ADDWF R2H,F
       BCF STATUS,C
D003:  RLF R0L,F
       RLF R0H,F
       DECFSZ R3L,F
       GOTO D002
       MOVF R0L,W
       RETURN
; Waitms Routine
W001:  MOVF R0L,F
       BTFSC STATUS,Z
       GOTO W002
       CALL W003
       DECF R0L,F
```

```
        NOP
        NOP
        NOP
        NOP
        NOP
        GOTO W001
W002:   MOVF R0H,F
        BTFSC STATUS,Z
        RETURN
        CALL W003
        DECF R0H,F
        DECF R0L,F
        GOTO W001
W003:   MOVLW 0x0C
        MOVWF R2H
W004:   DECFSZ R2H,F
        GOTO W004
        NOP
        NOP
        MOVLW 0x12
        MOVWF R1L
W005:   DECFSZ R1L,F
        GOTO W006
        CALL W007
        CALL W007
        NOP
        NOP
        RETURN
W006:   CALL W007
        GOTO W005
W007:   MOVLW 0x0D
        MOVWF R2L
W008:   DECFSZ R2L,F
        GOTO W008
        NOP
        RETURN
; Waitus Routine - Byte Argument
X001:   MOVLW 0x0A
        SUBWF R4L,F
        BTFSS STATUS,C
        RETURN
        GOTO X002
X002:   MOVLW 0x06
        SUBWF R4L,F
        BTFSS STATUS,C
        RETURN
        GOTO X002
; Waitus Routine - Word Argument
Y001:   MOVLW 0x10
        SUBWF R4L,F
        CLRW
        BTFSS STATUS,C
        ADDLW 0x01
        SUBWF R4H,F
        BTFSS STATUS,C
        RETURN
        GOTO Y002
Y002:   MOVLW 0x0A
        SUBWF R4L,F
        CLRW
        BTFSS STATUS,C
        ADDLW 0x01
        SUBWF R4H,F
        BTFSS STATUS,C
        RETURN
        GOTO Y002
; Adcin Routine
A001:   RLF R0L,F
        RLF R0L,F
        RLF R0L,F
        MOVLW 0x38
        ANDWF R0L,F
        MOVLW 0xC1
        IORWF R0L,W
```

```
        MOVWF ADCON0
        MOVLW 0x0A
        MOVWF R4L
        CALL X001
        BSF ADCON0,GO
A002:   BTFSC ADCON0,GO
        GOTO A002
        BCF PIR1,ADIF
        BCF ADCON0,ADON
        RETURN
; Lcdout Routine
LC01:   BSF 0x08,1
        BCF 0x08,2
        MOVWF 0x06
        BSF 0x08,3
        NOP
        BCF 0x08,3
        MOVLW 0x0A
        MOVWF R4L
        CALL X001
        RETURN
; Lcdcmdout Routine
LC02:   BCF 0x08,1
        BCF 0x08,2
        MOVWF 0x06
        BSF 0x08,3
        NOP
        BCF 0x08,3
        MOVLW 0x64
        MOVWF R4L
        MOVLW 0x00
        MOVWF R4H
        CALL Y001
        RETURN
; Lcdout Decimal Conversion
Routine
LC21:   BSF R3H,7
        MOVLW 0x27
        MOVWF R1H
        MOVLW 0x10
        CALL LC22
        MOVLW 0x03
        MOVWF R1H
        MOVLW 0xE8
        CALL LC22
        CLRF R1H
        MOVLW 0x64
        CALL LC22
        CLRF R1H
        MOVLW 0x0A
        CALL LC22
        MOVF R2L,W
        GOTO LC23
LC22:   MOVWF R1L
        MOVF R2H,W
        MOVWF R0H
        MOVF R2L,W
        MOVWF R0L
        CALL D001
        MOVF R0L,W
        BTFSS STATUS,Z
        BCF R3H,7
        BTFSC R3H,7
        RETURN
LC23:   ADDLW 0x30
        CALL LC01
        RETURN
; End of listing

END
```