DESIGN OF A RACE CAR TELEMETERING SYSTEM

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ABSTRACT

This student paper was produced as part of the team design competition in the University of Arizona course ECE 485, Radiowaves and Telemetry. It describes the design of a telemetering system for race cars.

Auto Racing is an exciting sport where the winners are the ones able to optimize the balance between the driver's skill and the racing teams technology. One of the main reasons for this excitement is that the main component, the race car, is traveling at extremely high speeds and constantly making quick maneuvers. To be able to do this continually, the car itself must be constantly monitored and possibly adjusted to insure proper maintenance and prevent damage. To allow for better monitoring of the car's performance by the pit crew and other team members, a telemetering system has been designed, which facilitates the constant monitoring and evaluation of various aspects of the car. This telemetering system will provide a way for the speed, engine RPM, engine and engine compartment temperature, oil pressure, tire pressure, fuel level, and tire wear of the car to be measured, transmitted back to the pit, and presented in a way which it can be evaluated and utilized to increase the car's performance and better its chances of winning the race. Furthermore, this system allows for the storing of the data for later reference and analysis.

KEYWORDS

Race Car, Transducers, A/D Conversion, Data Packaging and Synchronization, QPSK Modulation, Link Power Budget, Monopole and Dipole Antennas, Data Storage and Display, LabView

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INTRODUCTION

In auto racing it is important that the driver knows when is the optimum time to make a pit stop. Until now, pit crews and drivers have had to make educated guesses as to when to make the pit stops. A telemetering system has be designed to allow continual monitoring of the car's performance by the pit crew. This telemetering system will provide a way for the speed, engine RPM, engine and engine compartment temperature, oil pressure, tire pressure, fuel level, and tire wear of the car to be measured, transmitted back to the pit, and presented in a way which it can be evaluated and utilized to increase the car's performance and better its chances of winning the race. Furthermore, this system allows for the storing of the data for later reference and analysis, which will provide valuable insight to the driver's and pit crew's decisions made during races.

SENSORS

The sensors perform the incredible task of turning a mechanical or thermal quantity such as pressure or heat into an easily measurable and transmittable quantity such as voltage. They provide all information which will be transmitted and analyzed later on. Because of this, it is essential that the sensors are set up in a way that they will provide accurate and precise data.

First of all, two different sensors will be used to measure temperature. One of these sensors will be measuring the temperature of the coolant in the car's engine. The sensor used in this case is a temperature-sensitive thermocouple. The temperature sensor must have an operable range from 0°F to 400°F, to include any possible temperatures at which the engine may operate. Furthermore, these sensors should have a resolution of 0.1°F. A type "T" thermocouple has been chosen because it has a fairly linear behavior over a useful range of - 454°F to 752°F.

As mentioned earlier, the resolution of this sensor must be up to 0.1°F. From this, the required bit rate of the A/D converter can be calculated as follows:

$$2^N = \text{Range} / \text{Resolution} \tag{1}$$
$$\text{Range} = 400°\text{F} \tag{2}$$
$$\text{Resolution} = 0.1°\text{F} \tag{3}$$
$$N = \text{Log2}\ (400 / 0.\ 1) \tag{4}$$
$$N = 12 \text{ bits} \tag{5}$$

This indicates that the A/D converter's output will need to be at least 12 bits. The measurement provided by this temperature sensor will need to be provided 1 time per second. This equates to 1 sample per second and an output bite rate of 12 bits per second.

The next sensor to be discussed is the one which will be used to measure the ambient temperature of the engine compartment. This task will also be performed by a type “T” thermocouple. The ambient temperature of the engine compartment is a less vital statistic than the temperature of the engine itself. For this reason, the ambient engine compartment temperature will only be measured once every 10 seconds. This equates to 0.1 samples per second and an output bite rate of 1.2 bits per second.

The next subgroup of sensors are those which measure speed. The first will measure the speed at which the car itself is traveling. This will be accomplished by a dual-coil electromagnetic linear-velocity transducer. The range of car speed for which this sensor must measure is 0 to 300 MPH. The particular velocity transducer used in this instance will have an output voltage range going from 0 - 10 V. The resolution of the car speed measuring subsystem must be up to 0.1 MPH. The speed of the car is a very important piece of data which must be sampled 10 times per second, which equates to a bit rate of 120 bits per second from this A/D converter.

The revolutions per minute of the car’s engine, or the speed at which the engine itself is turning, is also a vital statistic of the car’s performance. For this sensor, a range going from 0 to 15,000 RPM must be detected with a resolution of at least 1 RPM. A transducer with output voltage varying from 0 - 20 V DC would be appropriate in this case. The bit rate of the A/D converter for this sensor is found to be 14 bits. The engine RPM will also be sampled at a rate of 10 samples per second, giving an A/D converter bit rate of 140 bits per second.

Oil and tire pressure are measured using a strain gauge. The range and resolution for the oil and tire pressure sensors are the same, range: 0 - 100 psi and resolution: 0.1 psi. The number of bits needed to achieve this resolution, similar to the previous sensor bit calculations, is n=10 bits. A higher sampling rate was used for the oil pressure due to the more critical nature of it to the car’s performance. Oil pressure is sampled 2 samples/sec, whereas, the tire pressure is sampled 1 sample/sec.

The fuel level sensor is accomplished using a differential-pressure transducer. Fuel level will be monitored with a range of 0 - 30 gallons and with a resolution of 0.1 gallons. Fuel level can not change very quickly, therefore, it only needs to be sensed at a sampling rate of 1 sample / sec. As shown in previous bit calculations, the number of bits needed to acquire the specified resolution and range is ten bits, n = 10.

Tire tread can be sensed by using optical sensors. A collimated source is mounted on the inner side of the wheel well. On the opposite side of the wheel well a photodiode is mounted. When the tire tread is a 100% the beam will be completely blocked by the tire and as the tire tread decreases the amount of light on the photo-diode will increase. Light on the photodiode will cause an output voltage across the diode, and as the amount of light on the diode increases the voltage across the diode will increase. Therefore, the tire tread is inversely proportional to output voltage across the photo-diode. Calibration of the output voltage and tire tread can be done, with 0 volts across the diode corresponding to 100% tire tread, and critical output voltage corresponding too little tire tread left and a pit stop needed.

Tire tread can be measured with a range of 0 - 2 inches and a resolution of 0.001 inches. In order to achieve these specifications, similar to the previous bit calculations, the number of bits needed is eleven bits, n = 11. The rate at which the tire tread changes is not extremely fast, thus a low sampling rate of 1 sample / 10 secs is used.

FRAME CONSTRUCTION AND SYNCHRONIZATION

The digital data produced by the payload sensors need to be put in a predefined format so that the receiver will recognize the sent data. Each sensor in the payload will occupy designated place in the frame. Each frame, called a major frame, contains minor frames with a defined format and number.

In the design of the car race telemetering system there are 8 types of sensors discussed in the sensors section. Each one of these sensors has a sampling rate which controls the frequency of which a certain parameter is measured. The minor frame used to package the data of the sensors is shown in figure 1. This format of the minor frame uses 8-bits words, so each block in the diagram except the first block, the synchronization, represents one word. The first sensor is the speed sensor which needs to be sampled 10 times each second. Each sample in the speed sensor has 12-bits. The RPM (Revolution Per Minute) sensor is sampled at 10 samples/sec. with each sample containing 14 bits. The speed sensor takes 15 words and the RPM sensor takes 17 words and 4-bits overflow which can share half a word with another sensor. The fuel level measurement is sampled at 1 sample/sec. and each sample is 12-bits. This can be put in one and a half words. The oil pressure sensor sampling rate is 2 samples/sec. with each sample containing 10-bits. This will take two words and 4 overflow bits that share half a word with the RPM. The tire pressure sensor sampling rate is 1 sample/sec. with 10-bits per sample which will take one word. Two bits share 1/4 word with the tire wear and ambient temperature. The engine temperature sampling rate is 1 sample/sec. and each sample is 12-bits; in frame words it will take 1.5 words sharing half a word with the overflow from the oil pressure sensor. The last two sensors are the tire wear and the ambient temperature sensors which have the same sampling rate of 0.1 sample/sec. and 12-bits per sample. Each one of these sensors will take 1-bit in the last word where 2-bits are already taken by tire pressure overflow which leaves 4 empty bits in the word.

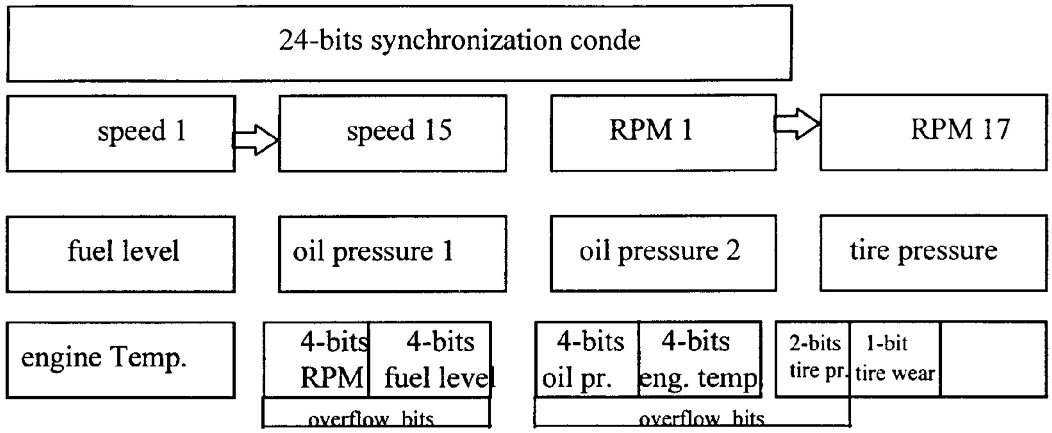

Figure 1. Minor Frame.

For the data produced by these sensors to be packaged properly, each sensor has to appear at least once per major frame. This can be achieved by packaging 12 minor frames in each major frame. Figure 2 shows the structure of the major frame.

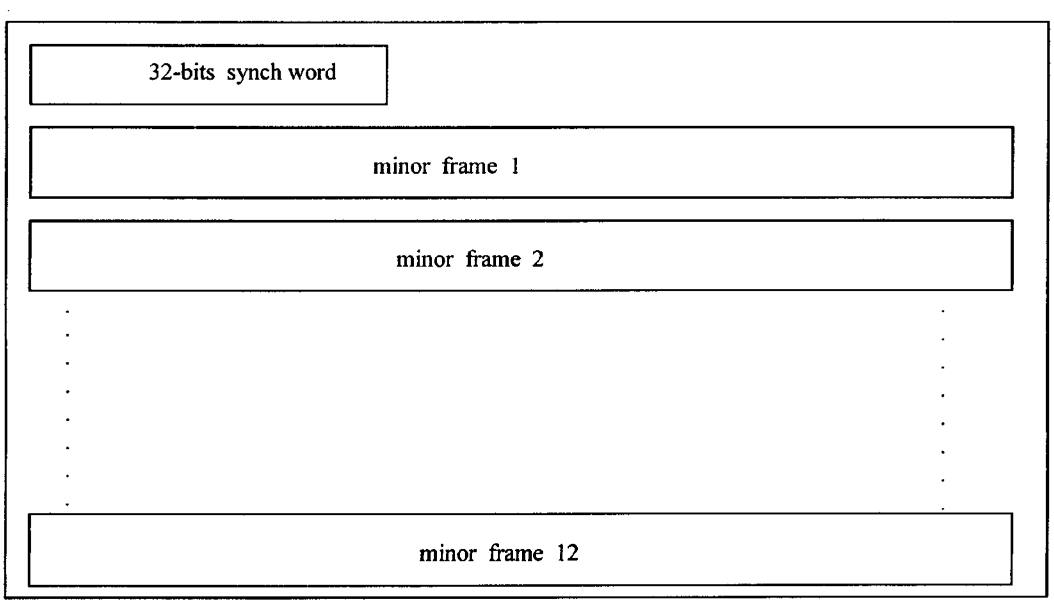

Figure 2. Major Frame.

To establish major frame and minor frame synchronization, synchronization codes are needed for each one. It is required to acquire a major frame synchronization with low false lock probability because of the large data it contains. For this reason, a 32-bit synchronization code is used with perfect correlation. With perfect correlation the probability of false lock is calculated by:

$$P_{fl} = 1/2^N \tag{6}$$

where is N is the number of bits in the synch. word. This will give us a probability of false lock of 2.33E-10 per second. A predetermined optimal synchronization code of 77465450200_8 is used [3].

For the minor frame synchronization, a 32-bit word is more than we need, therefore, a 24-bit synchronization code is needed for several reasons. First of all, it can take an increment of 8-bit words. The second is that with the high BER of 10^{-8} it would be rare to have errors that need more than 24-bit words. A predetermined optimal synchronization code of 7536263000_8 is used [3]. Perfect correlation is also used in searching for the synch. word for the minor frames. This will yield a false lock probability of 613-8 false locks per second.

MODULATION

The provision of reliable performance, exemplified by a very low probability of error, is one important goal in the design of a digital communication system. Another important goal is the efficient utilization of channel bandwidth. In this section, a bandwidth-conserving modulation scheme was studied. For that purpose, quadrature phased shift keying (QPSK) was chosen as the modulation scheme because it has low bit error rate, narrow bandwidth and low carrier power.

The in-phase channel makes a decision on one of the two bits constituting a symbol (dibit) of the QPSK signal and the quadrature channel takes care of the other bit. By doing some derivation, the bit error rate of QPSK is:

$$\mathrm{BER} = 1/2\ \mathrm{erfc}\left(\sqrt{\frac{Eo}{No}}\right) \tag{7}$$

BER is chosen to be : BER = 10^{-8} to reduce the bit error at the design.

Rb is chosen to be 1000 bps because the only data needed to be transmitted is the information that performs synchronization. A frequency of 1428 MHz is chosen since the car is mobile and is moving on land. The frequency range for this situation is 1427-1429 MHz. Bandwidth is chosen to be 0.5 MHz to satisfy the IRIG emission standard, and to ensure the data transmission efficiency.

ANTENNA DESIGN/MICROWAVE TRANSMISSION

The antenna for the telemetry system needs to be unobtrusive, therefore not hindering the aerodynamics of the race car. A small antenna such as the monopole is good for transmitting because of its broadband characteristics and simple construction. On the receiving end size is less of a factor, but still important. The dipole works well as a receiving antenna. It is also simple to construct and has similar characteristics to the monopole.

The antenna system requires a few other components other than the antennas. On the transmitting side, a transmitter and an amplifier (depending on signal strength and component gains) are required. The receiving end requires a low noise amplifier, down converter (mixer), amplifier and a receiver. These individual components are connected by coaxial cable.

The system temperature at the receiver is given by:

$$T_{sys,r} = (T_a + T_{LNA} + T_{AMP})\, G_{AMP} + T_{RCV} \qquad (8)$$

The carrier to noise ratio is the ratio of the received power level to the thermal noise power:

$$\frac{C}{N} = \frac{EIRP}{Ls} \frac{G_r}{T_{sys,r}} \frac{1}{kB_r} \qquad (9)$$

The energy per bit to unit bandwidth noise power ratio is shown as:

$$\frac{E_b}{N_o} = \frac{C}{N} \frac{B_r}{R_b} \qquad (10)$$

Table 1 shows the calculated values of the link power budget.

TABLE 1
Link Power Budget Values

Component	Value	Value(dB)
C	6.923E-10	-91.597
N	1.202E-13	-129.201
C/N	5.762E3	37.605
E_b/N_o	2.88 1 E6	64.595

A reasonable minimum fade/attenuation margin is found by calculating the energy per bit to unit bandwidth noise power ratio in decibels as:

$$\left[\frac{E_b}{N_o}\right] = [EIRP] + [G_r] - [L_s] - [kT_{sys,r}] \tag{11}$$

The calculated value is 88.097dB. Assigning a minimum fade/attenuation margin of 15dB will provide link closure. This will give a link power budget E_b/N_o = 79.595dB, which is far below 88.097dB.

A summary of calculated antenna values is shown in Table 2.

TABLE 2
Final Specifications

Component	Specification
Transmit EIRP	7.818dBW
Receiver Tsys,r	1.741E4K
Link Distance	max@ 2km
Receiver Bandwidth	0.5MHz
Operating Frequency	1428MHz
Minimum BER(QPSK)	E-8
Minimum Fade /Attenuation Margin	15dB
Data Rate	1 Kbps

DATA STORAGE AND DISPLAY

The final phase of the design will include a complete data storage and display facility. With the increasing availability of Commercial-Off-The-Shelf (COTS) software that can complete these requirements and the low overhead needed to run them, it is fairly easy to design and build an efficient, cheap, and practical interface system.

All interface design requirements are met with a COTS product, called Labview. Labview is a graphical software utility based on C programming language, however it is such a high-level language, that the user does not need to know any of the underlining principles of C.

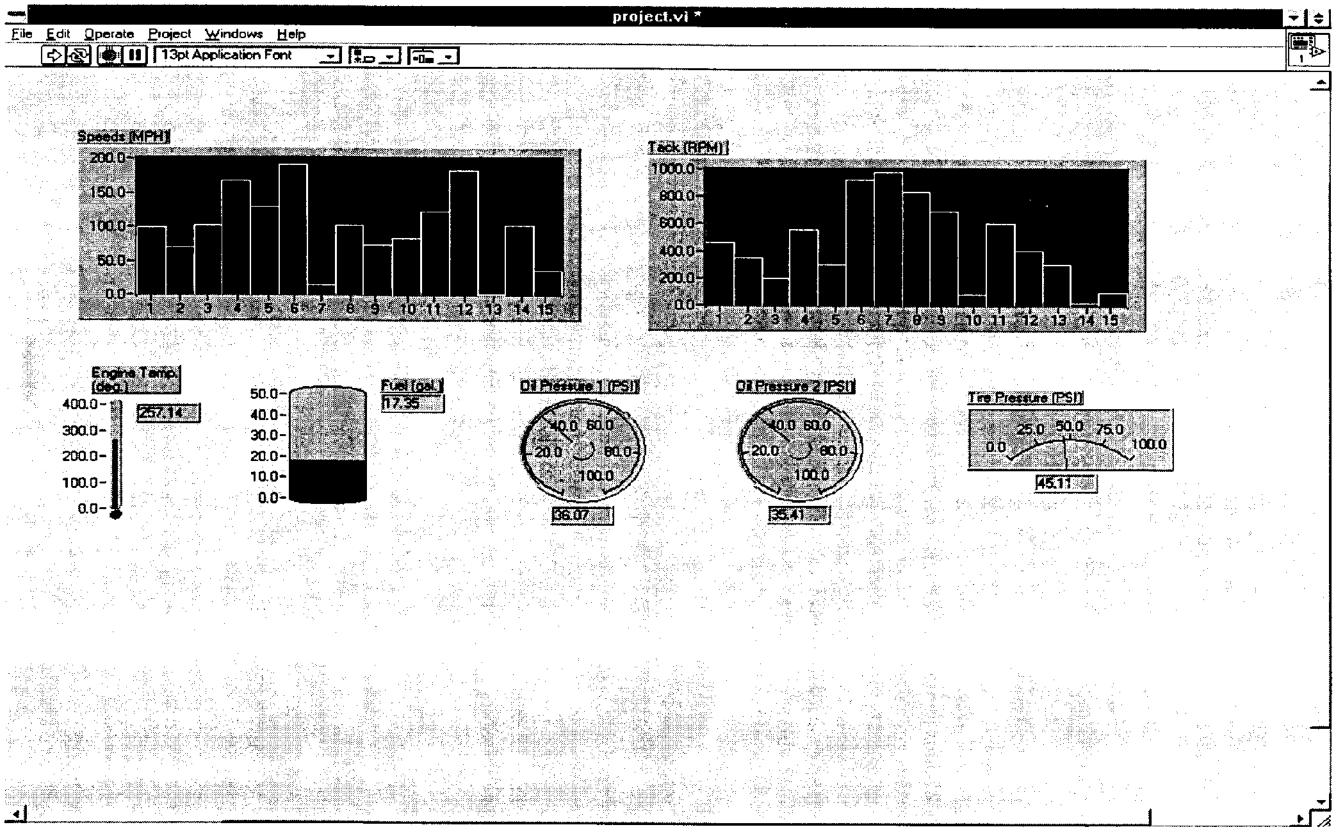

Figure 3: Graphical Interface displaying sample data read from frames.

The data in the frames transmitted includes speed, revolutions per minute (RPM), fuel level, oil pressure, tire pressure, engine temperature, ambient engine compartment temperature, and tire wear. These quantities are easily sorted in Labview given the frame format, and an example of the data display is given in figure 3. The speed of real-time updates in the display depends solely on the environment that Labview is running on, which is outlined for this design in the hardware section. The software can be used to check data for limiting values, predict future values, or use a combination of any parameters to calculate relevant information, such as speed and fuel level to display percentage of fuel being burned. The user could easily add to the display to customize, for example it would be trivial to add a button that lights up when the engine temperature reaches a critical value, telling the pit to warn the driver.

CONCLUSION

The designed telemetering system provides a means to monitor the driver's and the car's condition and help make decisions on when pit stops are needed. This will increase the safety to all drivers. No longer will there be a car on the track that does not have the safe amount of tire tread to allow proper traction. For example, a car that has just sprung an oil leak will detected by the pit crew with the oil pressure sensor. The pit crew can then flag in the driver and prevent the car from spreading oil on the track causing unsafe driving conditions, and possibly saving the engine from any permanent damage. Monitoring of the car will allow the pit crew to make informed decisions of when the driver should make a pit stop. This system will also allow analysis of the pit crew's decisions and driver's techniques used in past races. The driver will now be able to concentrate on his driving, rather than on monitoring the car's conditions. Remote sensing of the car's condition will increase the safety in the racing industry and raise auto racing to the next level of competition.

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