An Embedded System for Pollution Control in Automobiles by Using a MEMS Accelerometer Signal

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Abstract

In this paper an embedded system for the pollution control in automobiles is described. In particular, the focus is on the description of the control algorithm, which receives, as an input, a signal from a MEMS accelerometer and uses it to control the fuel injection rate, in order to reduce the toxic emissions from the exhaust gases. A DSP implementation and simulation results of the same are detailed.

1. Introduction

The large amount of air pollution caused by toxic emissions from automobile exhausts has always been a matter of grave concern. Automobile engines have an optimum stoichiometry for the air to fuel ratio for the mixture of air and fuel which, if maintained, results in complete combustion of the mixture in the engine [3]. This complete combustion of the fuel produces emission of only carbon dioxide and water vapor which are not toxic.

A parameter lambda is defined as the ratio of the actual air to fuel flow rate to the aforementioned optimum stoichiometry [2]. For normal automobile operations this ratio varies from 0.8 to 1.3, thus making a trade-off between power efficiency and pollution produced. However, more stringent conditions would require the precise regulation of this parameter to a value very close to unity. The state of the art technique for pollution control from automobile exhausts uses gas sensors [6] and catalytic converters [2]. There are gas sensors for oxygen, carbon monoxide, nitrogen oxides and also oxides of sulfur. On sensing the presence of these gases in the exhaust emissions catalytic converters like the three-way catalytic converter (TWC), converts the harmful gases into less toxic ones like carbon dioxide and water vapor. However, this approach has an inherent disadvantage in that it senses the pollution once it is produced and then attempts to reduce it by converting the harmful gases into less harmful ones. Essentially this approach is a curative technique and can not restrict the loss of the excess fuel that does not get converted into acceleration of the vehicle in spite of being injected into the engine, thereby reducing the fuel efficiency of the engine.

The novel approach for automobile pollution control described in this paper is more of a preventive measure. This work relates the rate of fuel injection to the acceleration produced by the engine and regulates the desired acceleration of the driver to the optimum value supported by the particular air to fuel ratio that will cause minimal pollution, along with complete combustion of the entire amount of fuel that is injected into the engine. As is evident from the figure 1, the carbon monoxide content in the exhaust reduces to a minimum when lambda attains a value of unity signifying the onset of complete combustion of the fuel hydrocarbons producing non-toxic carbon dioxide and water vapor. Thus, the control system described here does not allow an excessively high fuel injection rate into the engine that will decrease the value of lambda much below unity. This is achieved by using a control system named as the 'controller'. The first part of the controller, called the reference shaper, provides a variable threshold corresponding to the optimum fuel injection rate and the second part, called the control unit, makes the actual acceleration of the car track the output of the previous unit. The full control system is simulated on Simulink and tested on a simulated signal. A novel MEMS accelerometer is used to get the information about the actual acceleration of the automobile to be controlled.

In this paper are discussed both the implementation of the system on a DSP processor and the obtained performance. Our choice is motivated by the fact that embedded systems are gaining interest for their ability to implement real-time computing systems, and in particular automotive is one of the fields where emerging technologies like DSPs or Field Programmable Gate Arrays (FPGAs) are extensively used. The use of electronics in automobile process control is widely applied. In this context, our work is towards the design of a complete System–on–Chip (SoC),

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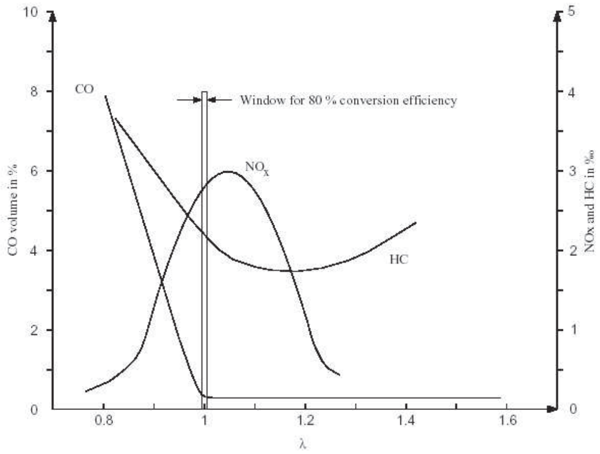

Figure 1. The concentration of different exhaust gases as a function of lambda (from [2])

for the control of automobile pollution, to be integrated inside the automobile itself. In this sense, this work is a kind of prototype in order to realize a full–custom integrated and compact design.

Thus, an embedded system is realized for the control system which receives the acceleration of the automobile from the MEMS accelerometer and then controls it in order to minimize air pollution without wastage of fuel.

This paper is organized as follows. In the next section the whole system is described. In particular, we provide details on the system components with a particular focus on the control system. In section 3 simulation and implementation results are detailed. In the end, we discuss the conclusions and future research in this area.

2. System components

The architecture level block-diagram of micro-electro-mechanical system for automobile pollution control is shown in figure 2. It mainly consists of :

- a MEMS accelerometer
- a low noise amplifier
- a high precision analog to digital converter
- a DSP implementing the controller
- a digital to analog converter
- an actuator

The MEMS accelerometer produces an analog signal corresponding to the present acceleration of the vehicle. This analog signal is very small in magnitude, about a few milivolts and it has to be amplified through a low noise amplifier (LNA). This low noise amplifier also acts as a low-pass filter which is required to nullify the effects of sudden jerks and impulses which produce high frequency signals.

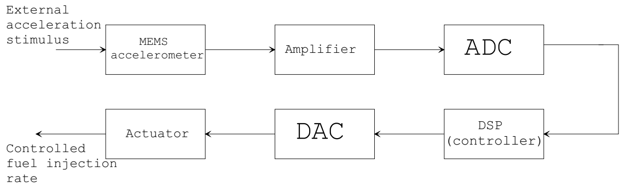

Figure 2. Block diagram of MEMS driven pollution control system in automobiles.

Then, the output from the LNA is fed into a precision analog to digital converter (ADC). It produces fairly accurate results in the given range of voltages with very little quantization loss.

The digital output from the ADC is fed into an algorithm, which compares its present value with the optimum value of acceleration and velocity of the particular vehicle and produces a corresponding error signal. At the heart of the control algorithm there is basically a PID controller, with some modifications. It tracks the desired acceleration of the driver and smoothly brings it down to the level of the optimum acceleration that is supported at that speed and torque situation, so that the pollution is reduced to zero.

The algorithm has been implemented and tested in SIMULINK. As the next step it has been downloaded and implemented on a DSP processor. The error signal produced is used to compensate for the excessive fuel injection into the engine by an actuator.

The actuator is basically a synchronous motor that works according to the error signal produced by the controller and reduces (or increases) the pressure difference between the fuel tank and the combustion chamber to decrease (or increase) the rate of fuel injection and hence the acceleration of the car. It is proposed that the control be done on the pressure applied on the reservoir of the fuel that controls the pressure difference between the top surface of the fuel and the pressure inside the combustion chamber. Then, by Bernoullis theorem, we can control the velocity and hence the rate of flow of the fuel into the combustion chamber.

This control of the pressure incumbent on the fuel top surface is achieved by using a crank shaft, which may be driven by the motor that will be run by the output of the controller.

2.1. The MEMS accelerometer

The micro–accelerometer, that is used as a sensor for the system, consists of a proof mass that is suspended from a frame by means of four thin flexures (see figure 3) [4]. The frame is attached to the system whose acceleration is to be measured. The flexures contain piezoresistors attached on them that are interconnected as the arms of a Wheatstone's bridge. On subjecting the device to an acceleration the flexures experience tensile and compressive stress and the bridge is no longer balanced. The voltage

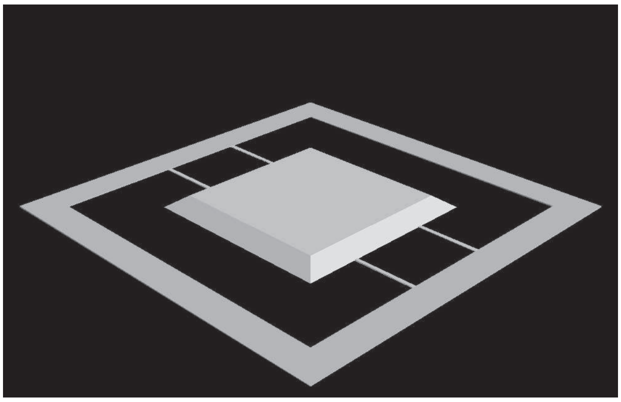

Figure 3. The MEMS accelerometer structure.

Table 1. Design specifications of MEMS accelerometer

Parameter	Specified Value
Acceleration rate	± 2 g
Machanical shock	50 g (on vehicle for 2 ms) 3000g (during ass. drop test)
Operating temperature	$-40°$ C to $+85°$ C
Supply voltage	5-10 V
Resolution	10 mg
Sensitivity	10's of mV/g
Cross Axis Sensitivity	$< 5\%$
Non–linearity	$< 2\%$
Band width	DC–400 Hz max (DC–100 Hz typically)
Sensing	PZR
Damping	Critical Air damping
Exposure	Humidity, Salt spray, Exaust gases

output across the terminals of the bridge is proportional to the acceleration ($V_0 \propto \Delta R$). The sensor basically works by utilizing the principle of piezoresistivity, and its main characteristics are reported in table 1.

2.2. Low noise amplifier

The output signal from the accelerometer is around 1 mV so it has to be amplified to about 5 Volts and hence a low noise amplifier is required. Also, to nullify the effects of sudden changes like jerks the signal needs to be filtered using a low-pass filter. The amplifier and filter is implemented using an instrumentation amplifier. The frequency range of the amplifier has to be within 0 to 1 kHz. Another challenging issue associated with the amplifier is to provide a fairly stable power supply of 5 V to the amplifier.

For the purpose of amplifying the transducer output the instrumentation amplifier has been used as it gives some distinct advantages over a differential amplifier configuration.

The amplifier designed is a low-pass amplifier and works very well for low frequencies, which are as low as 35 Hz, below which the amplifier could not be tested for limitations in triggering of the oscilloscope. The cut-off frequency of the amplifier is around 3.2 kHz as is evident from the plot of gain Vs frequency, as shown in figure 4

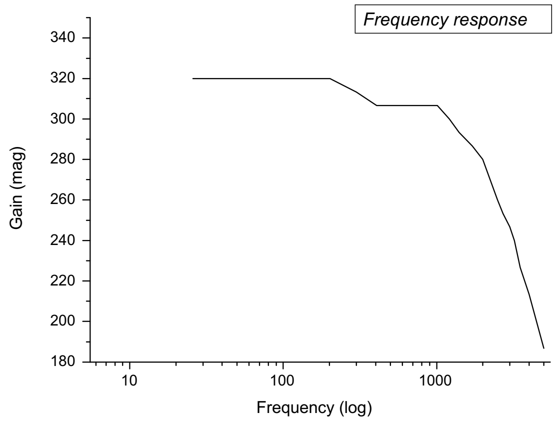

Figure 4. Frequency response of the amplifier.

2.3. The Analog to Digital converter

The output from the amplifier is fed to an integrator to estimate the velocity of the vehicle. Then the output from the integrator is fed into a precision sigma-delta analog to digital converter. It is a 16-bit ADC. Thus, it produces fairly accurate results with the given range of voltage with very little quantization loss.

The sigma-delta converter is to be used because of its:

- high resolution;
- noise shaping characteristics of the modulator, basically the quantization and the low frequency noise.

The output of the amplifier is a very low frequency signal and the ADC that should not introduce noise, nonlinearity due to quantization and the converter resolution as well should be higher. Experiment in the ADC part is going on to make a comparative study between sigma-delta converters and other high speed flash converters towards the implementation in a full custom SoC.

2.4. The Control Logic

The block diagram of the control logic used in controlling the automobile pollution is shown in figure 5. As it is shown in the figure the controller has two parts, namely a reference shaper, that shapes the intended acceleration according to a rule and a controlling section called the control unit, that regulates the acceleration by a control algorithm.

The intention of the driver is sensed as the acceleration which is requested. For the purpose of the simulation

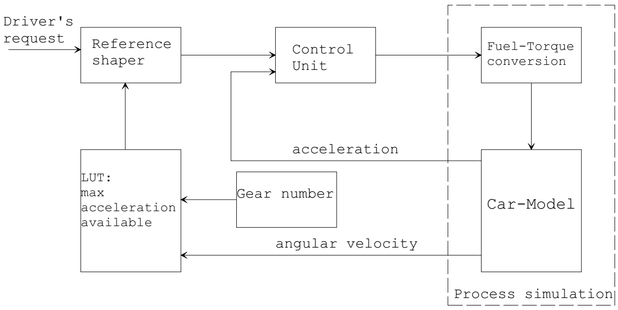

Figure 5. The controller for Simulink simulation.

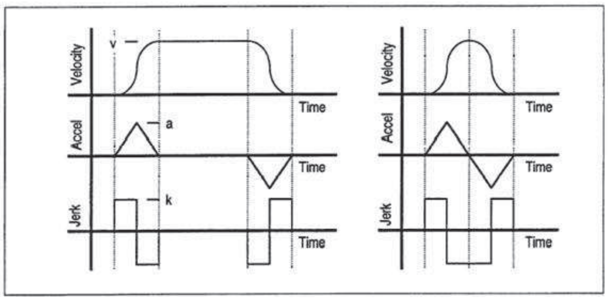

Figure 6. Velocity and acceleration profile considered.

here a skewed triangular pulse is used that is taken as a typical example of a drivers requested acceleration. The requested acceleration is measured in units of acceleration due to gravity (g) and is assumed to vary from zero to a high peak and reduce to zero again. There have been efforts for modeling driver behavior using neural networks based on 'car–following' algorithms [1]. However, here we use a simplified desired acceleration profile to test our approach. The acceleration experienced by cars generally vary around 3 to 4 m/s^2, that is roughly less than 0.5 times the acceleration due to gravity (g) [7]. However, certain racing vehicles are known to have very high performance giving very high accelerations of a value close to 3 times g [8]. The system that we have designed has flexibility as it can be used for different vehicles with different thresholds by changing only a few parameters. A generic profile showing the relationship between the typical velocity and the acceleration, as well as the jerk experienced by the car is shown in the figure 6. This steep signal is then passed through a reference shaping unit, that shapes the curve in such a way that it does not exceed the maximum acceleration supported by the car for the current running conditions of velocity and gear number. This maximum supported acceleration is received as an input to the reference shaping unit from a look-up table that maps the car dynamic conditions like current angular velocity of the wheels and the gear number to the variable threshold for acceleration. This maximum acceleration that can be supported by the car is the threshold beyond which the particular automobile can not go even if the rate of injection of fuel is increased. The shaping unit is a sigmoid shaping function that clips the intended acceleration smoothly and keeps it below the maximum possible acceleration.

After the requested acceleration is shaped smoothly according to the maximum acceleration, it is fed as an adaptive threshold to the control unit that now controls the acceleration of the car. This control unit consists of a PID controller that receives as an input the shaped input reference which is used as the adaptive set-point for the controller and the measured acceleration from the MEMS accelerometer, that is installed in the car which is the process. The control algorithm generates an error signal that is subtracted from the requested acceleration, which then produces a corrected acceleration that is sensed by the accelerometer. This corrected signal is actually converted into a fuel injection signal that controls the rate of fuel injection and hence controls the acceleration. The output of the controller is a signal that drives a synchronous-motor to regulate the pressure difference between the fuel-reservoir and the combustion chamber, thus regulating the rate of fuel-injection. This controls the torque generated, which in turn produces angular acceleration of the wheels and thus acceleration of the car. In the following we show the discrete control algorithm [5]:

$$\begin{aligned}&\mathrm{OutP(n)} = \mathrm{OutP(n-1)} + \mathrm{Gain} * [\{\mathrm{Err(n)} - \\ &\mathrm{Err(n-1)}\} + \mathrm{Ki} * \{\mathrm{Err(n)}\} + \\ &\mathrm{Kd} * \{\mathrm{Err(n)} - 2 * \mathrm{Err(n-1)} + \mathrm{Err(n-2)}\}]\end{aligned} \tag{1}$$

where:

- $Err(n) = Inp(n) - SetP$, error at the nth instant
- $Inp(n)$, input at the nth instant
- $OutP(n)$, output at the nth instant
- $SetP$, variable set point
- $Gain$, proportional control coefficient
- Ki, integral control coefficient
- Kd, differential control coefficient

The above formula has been obtained by differentiating the expression for a PID controller and then subsequently discretizing it for ease of implementation on a digital signal processor.

The Look Up Table (LUT) for the mapping between the current angular velocity of the wheels and the gear number in use, is dependent on the particular model of the automobile and is yet not available in details. But the simulation test has been carried on with an example table giving a typical behavior for a fixed gear.

To convert the fuel injection rate information into the torque we need another look-up table that the manufacturers provide in the processors of the cars. This table is also approximated and used for the time being and will be fed

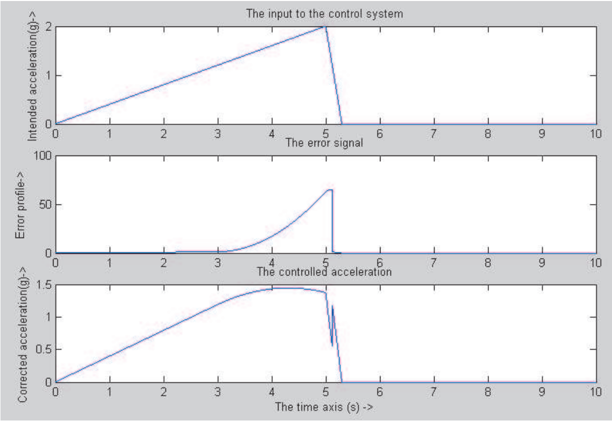

Figure 7. The error signal and the controlled acceleration by only the algorithm, for maximum acceleration equal to 2g.

with exact data later depending on the particular vehicle model.

The car model used for the simulation purpose consists of a gain block that takes as an input the torque generated by the IC engine and gives the angular acceleration by dividing the torque by the moment of inertia of the rotating shaft and the piston. A typical value for that moment of inertia is chosen as 900 slags-square ft. This angular acceleration multiplied by the radius of the wheels gives the linear acceleration of the car as sensed by the accelerometer. In the model, however, another block is required to convert the acceleration from SI units to units of g or acceleration due to gravity. On the other hand, the angular acceleration on integration in the discrete domain gives the angular velocity, that is used in the feedback loop to give the optimum acceleration from the look-up table of angular velocity to torque conversion [10]. The torque input to the model comes from the ROM provided by the manufacturers of a particular vehicle type, that converts a particular fuel injection rate into the optimum torque and that gives maximum power under that condition. This model, however, is simplified as the resistive forces like friction and braking are not included [11].

3. Simulation and implementation results

In this section we report the simulation and the implementation results. We used MATLAB 6.5 and Simulink to simulate the control unit and the entire controller, respectively. Then, the whole system has been implemented on the E6711 DSK Texas Instruments board, which includes both the ADC and the DAC with a fixed sampling rate of 8 kHz. As an intended acceleration a profile has been used which is an asymmetric triangular pulse as it is statistically a typical shape, as indicated in the previous section. The implementation of the control algorithm alone on MATLAB has produced the results shown by the plot in figure 7. This result is obtained using a fixed set–point for the control unit, which for this particular simulation is taken to be 1.2 times 'g', while the maximum acceleration as been fixed to 2g. The error profile and the corrected acceleration after error compensation using the variable threshold from the reference shaper output, as an adaptive set–point for the control unit, is shown in figure 8. In figures 9–10, we report a different simulation. In this particular simulation we have taken the maximum desired acceleration of the driver as 0.5 times 'g' and the optimum threshold for the car as 0.3 times 'g' keeping in mind the average figures. This is a standard operative condition.

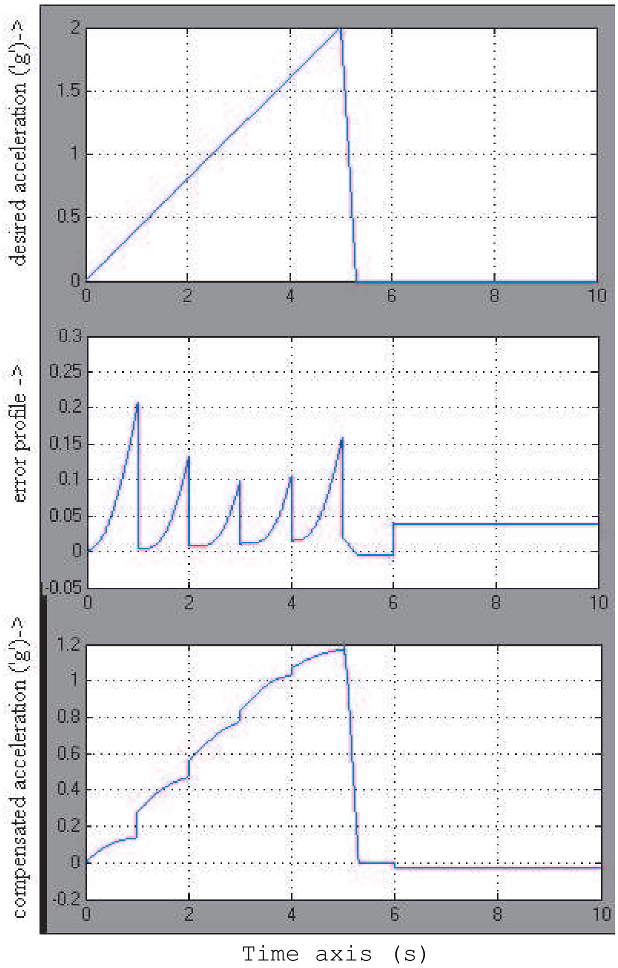

Figure 8. Results from Simulink simulations of the entire controller, for maximum acceleration equal to 2g.

The plots show that the desired acceleration tracks the intended profile. In particular, in the first simulation, we supposed that the driver intends a sharp rise in the acceleration from zero to two times g (acceleration due to gravity) and then releases the accelerator and hence the acceleration falls to zero again due to resistive forces. The error signal rises as the desired acceleration crosses the variable threshold, as set by the reference shaper within each

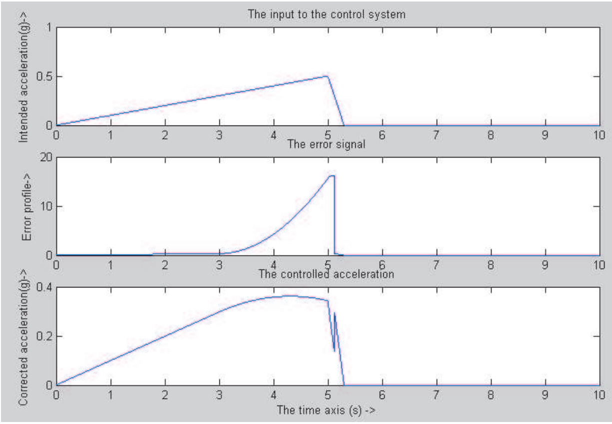

Figure 9. The error signal and the controlled acceleration by only the algorithm, for maximum acceleration equal to 0.5g.

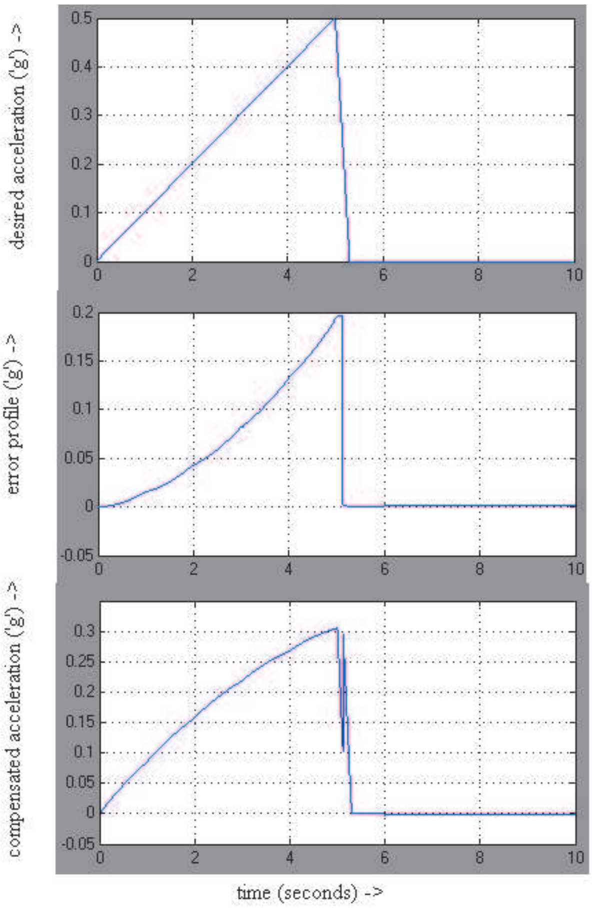

Figure 10. Results from Simulink simulations of the entire controller, for maximum acceleration equal to 0.5g.

sampling interval of one second. It gradually limits the intended acceleration to the threshold. In the final corrected acceleration plot we see that the acceleration is limited to the maximum acceleration supported by the car for that road condition and that gear number, which is set at 1.2 times g, in this particular case. The second simulation is similar to the previous one, thus showing the robustness as well as the flexibilty of the system implementing the algorithm.

One important point to be noted is that the sampling time for the output from the reference shaper has to be much larger than the period of processing for the PID controller. The sampling time for the reference shaper should be in the order of 1 second whereas the sampling time for the controller part is put at an approximate value of 0.02 second. This value is convergent with the mechanical response time for the fuel injection actuator which varies from 4 to 10 ms. This difference between the sampling periods of the reference shaper and the control unit is incorporated in the model of the control system. Thus, the sampling period of the reference shaper output is kept at 1 second which is a practically feasible estimate.

The parameters of the PID controller have been empirically deduced. Experiments have shown that optimal values are $K_I = 0.1$, $K_D = 0.5$ and $Gain = 1.5$, for the first simulation, while in the second the values of the parameters are $Gain = 0.75$ and the other two, i.e., Ki and Kd, remain the same. We observed that the parameter K_I has an influence on the compensation error, in fact as soon as K_I increases then the peaks of the error profile increases as well, thus reducing the smoothness of the compensated acceleration. By increasing the $Gain$ parameter we observed over compensation and the compensated acceleration never reaches the maximum allowed threshold. In the end, decreasing the parameter K_D enables faster and smoother tracking of the variable threshold. However this effect is almost marginal.

The implementation results were in accordance with the Simulink simulations, thus indicating the correctness of our approach. The system runs with a clock frequency of 100 MHz, the only one available on the board, and variables have been coded by using 16 bits.

4. Conclusions and discussion

In this paper we have described the components of an embedded system used for the pollution control of automobiles. The proposed novel approach uses the signal from a MEMS accelerometer measuring the acceleration of an automobile, and implements a control logic on that signal in order to regulate the fuel injection rate in such a way that the amount of unburnt hydrocarbons in the exhaust gases are reduced. As a consequence, the corresponding discrete control algorithm implemented on a DSP has been detailed.

The main goal of our research is the design of a compact integrated SoCs which embeds intelligent MEMS-based sensors. In this sense, this work can be intended as a step to produce a final full-custom-chip, where the analog part, strictly related to the MEMS, is interfaced with the digital processing units. So far the work has been done using a DSK and signals from a signal generator with the aim of developing a prototype that can be installed and tested on an actual engine in the future.

Later on it is planned to make a parallel implementation on FPGA in order to compare the performance of the two different implementations from different points of view. In fact, the FPGAs recently proposed (see for example the Xilinx Virtex–II and the Xilinx Virtex–IIpro [12]), permits one the design and the simulation of complete SoCs by using soft or hard processor cores (such as the Microblaze or the PowerPC) and powerful CAD tools. In this sense, now that the technology is mature, the FPGA–solution appears appealing.

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References

[1] J.Bengtsson, "Adaptive Cruise Control and Driver Modeling", Licentiate thesis, Department of Automatic Control Lund Institute of Technology, Lund, Sweden, 2001.

[2] P. Berggren and A. Perkovic, "Cylinder Individual Lambda Feedback Control in an SI Engine", Technical report, Reg. No. LiTH-LSY-EX-1649, http://vehicular.isy.liu.se, 1996.

[3] J.B.Heywood, Internal Combustion Engine Fundamentals, McGraw-Hill, 1988.

[4] S.Kal, "Micromachined Inertial Sensor for Linear Acceleration with Low off-axis Sensitivity", Proc. IWPSD-2003, International Conference, IIT Madras, India, December 2003.

[5] Katsuhiko Ogata, Modern Control Engineering, Pearson, 2002.

[6] J.B. Michel, C. Champinot and J. Dugue, "State of the Art on Emerging Combustion Control Sensors", Sixth International Conference on Technologies and Combustion for a Clean Environment, Oporto, Portugal, 9-12 July, 2001.

[7] P. Taruffi, The Technique of Motor Racing, Cambridge, Massachusetts, Robert Bentley, 1958.

[8] P. Zitzewitz, Merrill Physics Principles and Problems, New York, Glencoe, 1995.

[9] http://semiconductortechnology.net/p1.html

[10] http://www.tech.plym.ac.uk/sme/mech331/fuel3.htm.

[11] http://www.tech.plym.ac.uk/sme/mech331/partb1.htm

[12] http://www.xilinx.com.