Precision Wideband Controller V0.95
Questions/Answers for Hardware/Schematic

February 2004

Q: What is the Precision Wideband Controller?

A: The Precision Wideband Controller is a controller for wide-range lambda sensors (i.e. sensors which include a separate Nernst cell and oxygen pump cell).

Features include:

- Full-range operation of the pump circuit for full-range operation of the wideband sensor.
- Full-range operation of the sensor heater utilizing SEPIC switching power supply to ensure stable sensor temperature for any battery voltage.
- Analytical calculation of Lambda and AFR based on hydrocarbon information, water-gas equilibrium, and exhaust backpressure information.
- Automotive temperature range components used for **all** devices.
- Efficient circuitry eliminates the need for external heatsinking for power components.
- Stable voltage references utilized for precision.
- Extensive noise filtering on battery voltage to prevent noise entering or leaving the controller.
- Precision instrumentation amplifier used for pump current detection – best CMRR rating available.
- On-board thermocouple amplifier with cold-junction compensation for K-type thermocouples.
- On-board temperature monitor of DSP for over-temperature detection.
- CAN network interface.
- Very high-speed UART interface.

Q: There are many other Wideband Oxygen Controllers out there, why re-invent the wheel?

The reason for re-inventing the wheel is when the current wheel does not meet all of the needed requirements for a particular application. Read this entire document and this will become very clear.

Q: What is the difference between a Wideband Meter and a Mixture Feedback Controller?

When one is tuning an engine, be it on the road or on a dynamometer, it is desired to have a means of monitoring engine air-fuel ratio (AFR), which can also be expressed in terms of lambda. During these tuning sessions, engine/vehicle/environmental parameters are kept constant with the exception of the variable being tuned. Wideband Meters utilize a user-interface to obtain the current AFR/lambda such that the engine tuner can adjust and optimize.

A mixture feedback device is used to determine the instantaneous mixture of a running engine, where these parameters are introduced back into the fueling equation in the ECU for realtime injector pulsewidth correction. The main demand of the mixture feedback device is that it needs to be repeatable over absolutely all environmental conditions – the same readings for extreme hot or freezing cold conditions.

In addition, the response function of the wideband UEGO sensors are dependent on parameters like hydrocarbon type, operational temperature, exhaust temperature, exhaust backpressure, etc. – if any of these parameters change, then the controller needs to know this and be able to correct/compensate.

The Precision Wideband Controller is a mixture feedback device.

Q: Explain the operation of the wideband UEGO sensor

Yes, yes, yes – before one can design hardware circuitry and control software, an understanding of how the wideband UEGO sensor operates is required.

The wideband exhaust gas oxygen sensor comes in many constructional forms, but are basically similar in nature. They consist of two parts: a Nernst reference cell and an oxygen pump cell, co-existing in a package that contains a reference chamber and heater element (used to regulate the temperature of the Nernst/pump).

Before delving deeply in the operation of the Nernst and pump cells, it is important to understand what the sensor is actually trying to measure. To start, lets understand the chemical reactions due to combustion. First, realize that for combustion to occur, there needs to be **fuel** (such as hydrocarbon) and a source of **oxygenates** (i.e. oxygen and/or molecules or partial molecules which contain oxygen). In addition, there are **diluents** which are present in the mixture but do not contribute to the actual combustion (for example, nitrogen). This holds true for any combustion event, be it inside of an internal combustion engine or a small campfire. Second, everything is conserved in the combustion process, so it is possible to use exhaust gas constituents to reconstruct the amount of fuel and oxygenates before combustion. If this was not the case, then wideband oxygen sensors would not be capable of determining pre-combustion air/fuel ratio.

It is possible to express the combustion event as a balance of input reactants: fuel, oxygenates, and diluents (for example gasoline mixed with air) to the resultant combustion products (i.e. the composition of exhaust gas). Note that this is a chemical **balance**, meaning that every element needs to be accounted for in its molecular balance, before and after the combustion event. In other words, if we know the proportions of fuel, oxygenates, and diluents entering the engine, one can determine the species composition in the exhaust gas. And, we can work backwards – if we know the species in the exhaust we can determine the ratios of air and fuel (both in molar quantity and molecular mass).

Let us represent the chemical composition of the intake fuel as carbon, hydrogen, oxygen, and nitrogen, in proportion of $\mathbf{C_\alpha\, H_\beta\, O_\gamma\, N_\delta}$, with α, β, γ, and δ representing the amount of each of the elements present (i.e. moles of each element). For example, octane has a molecular composition of $C_8\, H_{18}$, so there are 8 moles of carbon and 18 moles of hydrogen, so we have α=8, β=18, γ=0, and δ=0.

We can combine this fuel with air and write down a simple balance equation for combustion and balance for the number of atoms before and after combustion:

$$\varepsilon[C_\alpha H_\beta O_\gamma N_\delta] + (x_O O_2 + x_n N_2) \rightarrow \nu_1 CO_2 + \nu_2 H_2O + \nu_3 N_2$$

The items on the left side of the arrow represent the fuel/oxygenates/diluents entering the engine and the items on the right are the molar quantities after the combustion event. We want to solve for the unknowns ε, which is the molar fuel-air ratio (equivalency ratio) and the coefficients ν_1, ν_2, and ν_3 that describe the product composition. The variable x_o represents the molar fractional percentage of oxygen in the intake air (0.21 is a commonly used value) and x_n represents the molar fractional percentage of nitrogen (0.79 is often used).

Note that we have more unknowns than equations, so we will have to use some known constraints to help us solve for the unknowns. For one, atoms are conserved (i.e. what goes in must come out), so we can immediately write the following relations (known as the element balance equations):

$$\begin{aligned}
&Carbon: \varepsilon\alpha = \nu_1 \\
&Hydrogen: \varepsilon\beta = 2\nu_2 \\
&Oxygen: \varepsilon\gamma + 2x_o = 2\nu_1 + \nu_2 \\
&Nitrogen: \varepsilon\delta + 2x_n = 2\nu_3
\end{aligned}$$

The solution for the balance equations (listed above) are the following:

$$\nu_1 = \frac{0.210\alpha}{\alpha + 0.25\beta - 0.5\gamma}$$

$$\nu_2 = \frac{0.105\beta}{\alpha + 0.25\beta - 0.5\gamma}$$

$$\nu_3 = \frac{0.790 + 0.105\delta}{\alpha + 0.25\beta - 0.5\gamma}$$

$$\varepsilon = \frac{0.210}{\alpha + 0.25\beta - 0.5\gamma}$$

And from this one can write the stoichiometric fuel-air mass ratio as:

$$F_s = \frac{\varepsilon[12.01\alpha + 1.008\beta + 16.00\gamma + 14.018\delta]}{28.85}$$

Note that the stoichiometric mass air-fuel ratio is simply the reciprocal of the above equation. Also, the fuel-air equivalence ratio is defined as the actual fuel-air ratio divided by the stoichiometric fuel-air ratio (note that the reciprocal of this is defined as lambda):

$$\phi = \frac{F}{F_s} = \frac{1}{\lambda}$$

Now, since we are dealing with exhaust gas (i.e. low temperature compared to the actual combustion event) and carbon-to-oxygen ratios less than unity, one can introduce CO and H2 into the balance:

$$\phi\varepsilon C_\alpha H_\beta O_\gamma N_\delta + (0.21 \cdot O_2 + 0.79 \cdot N_2) \rightarrow \nu_1 CO_2 + \nu_2 H_2O + \nu_3 N_2 + \nu_4 O_2 + \nu_5 CO + \nu_6 H_2$$

Kinda hard to solve this, but know a few things can make our life easier. First, if the mixture is lean (i.e. $\phi < 1$) then ν_5 and ν_6 are zero. For rich mixtures, $\nu_4 = 0$. And, for the rich case, we can introduce the water-gas equilibrium constant for the reaction:

$$CO_2 + H_2 \leftrightarrow CO + H_2O$$

which yields the constant K_p:

$$K_p(t) = \frac{P_{CO} * P_{H2O}}{P_{CO2} * P_{H2}}$$

With this, ν_5 can be evaluated as a solution to a quadratic:

$$\nu_5 = \frac{-b+\sqrt{b^2-4ac}}{2a}$$

where:

$$a = 1.0 - K_p$$
$$b = 0.42 - \phi\varepsilon(2\alpha - \gamma) + K_p[0.42(\phi - 1) + \alpha\phi\varepsilon]$$
$$c = -0.42\alpha\phi\varepsilon(\phi - 1)K_p$$

Using this result, a chart outlining the solution for each gas species can be tabulated for either lean or rich situations:

i	Species	$\phi < 1$	$\phi > 1$
1	CO_2	$\alpha\phi\varepsilon$	$\alpha\phi\varepsilon - \nu_5$
2	H_2O	$\beta\phi\varepsilon/2$	$0.42 - \phi\varepsilon(2\alpha - \gamma) + \nu_5$
3	N_2	$0.79 + 0.5\delta\phi\varepsilon$	$0.79 + 0.5\delta\phi$
4	O_2	$0.21(1-\phi)$	0
5	CO	0	ν_5
6	H_2	0	$0.42(\phi - 1) - \nu_5$

There are a few things to note in all of this. First, the hydrocarbon/fuel specified as $C_\alpha H_\beta O_\gamma N_\delta$ can be the combination of two or more hydrocarbons. For instance, when fuels are mixed with alcohol, the resulting mixture can be expressed as a single hydrocarbon with balanced subscripts. The same is true for water injection or nitrous oxide injection. This is a very important advantage in using a mathematical approach to determining lambda – if the fuel component changes it is possible to adapt the response of the wideband appropriately without any recalibration. This is not the case with systems that rely on a fixed wideband sensor response "curve". And, if the wideband controller is connected to a ECU (via CAN bus) and the ECU is controlling the introduction of water or nitrous, it is possible to instantaneously adjust the lambda response curve for any ratiometric combinations of hydrocarbons. This is an important requirement for a mixture controller.

Next, one can divide the hydrocarbon/fuel expression by a constant, which will make the carbon subscript equal to one. This creates a H/C ratio, a O/C ratio, and a N/C ratio – these are often seen in the literature. For example, the fuel C_8H_{18} can be normalized to become $CH_{2.25}$, where the H/C ratio is 2.25, the O/C ratio is 0 (there is no oxygen component) and N/C of 0 (no component), and, of course, the C subscript is 1. Another example is the fuel CH_3NO_2, which already has a C subscript of 1, so the H/C ratio is 3, the N/C ratio is 1 and the O/C ratio is 2. Just note that either form of expressing the fuel is identical.

Note: For those who are interested in experimenting with the above equations, we have developed the program COMBAL, a PC application running under Windows. One basically enters the H/C and O/C ratios, exhaust gas equilibrium, and the target lambda, and it generates the percent moles of each of the gas species. A comparison check using Brettschneider is also performed. The application can be downloaded from:

www.bgsoflex.com/pwb/combal.zip

Are you confused yet? If you are, do not be concerned. All we are outlining here is that with known input fuel, diluents, and oxygenates, one can predict the gas concentrations in the exhaust. And, yes, we can go backwards – with measured gas constituents it is possible to determine the input mixture in terms of either lambda or air/fuel ratio. Go back and re-read the section a few times, it is important to understand this aspect.

There is much more to the analysis not shown here – see the Bowling & Grippo paper on the entire analytical method for the Precision Wideband Controller for more info.

Lets move on. Now lets attempt to understand the operation of the Nernst cell section of the UEGO. The Nernst cell is an electrochemical cell consisting of a solid electrolyte conductive only to oxygen ions. Attached to this electrolyte are two platinum electrodes. One electrode is exposed to atmosphere and the other is exposed to a reference chamber (more on this later).

At the electrodes, the following reactions occurs:

$$\text{Cathode: } \mathrm{O}_{2(g)(atmosphere)} + 4e^{-} \rightarrow 2\mathrm{O}^{2-}_{(electrolyte)}$$
$$\text{Anode: } \mathrm{O}^{2-}_{(electrolyte)} \rightarrow \mathrm{O}^{2-}_{(g)(exhaust)} + 4e^{-}$$

With this reaction 'going on', a current can be generated. Using the Nernst equation, one can calculate the EMF produced under a no-load situation:

$$E = -\frac{RT}{zF}\ln\left[\frac{p_{o2\_test}}{p_{o2\_ref}}\right]$$

Where E is the "Nerstian EMF generated,
R is the Universal Gas Constant = 8.31 $J^*K^{-1}*mol^{-1}$,
T is the temperature of the cell in Kelvin,
F is the Faraday Constant = 96500 $Cmol^{-1}$,
Z is the electrons transported per O_2 = 4.

Because there is a heater maintaining the Nernst cell at an elevated temperature, a temperature gradient exists which generates an offset voltage. We can add this term to the above term, and in the process we can also simplify the calculation by converting from base e to base 10 logarithms:

$$E = -2.303\frac{RT}{4F}\left[\log_{10}\left(\frac{p_{o2\_test}}{1atm}\right) - \log_{10}\left(\frac{p_{o2\_ref}}{1atm}\right)\right] + Eoffset$$

Now that we know the operation of the Nernst cell, a little on the physical construction is in order. The UEGO sensor is of a "planar structure" – this means that it is in a rectangular form as opposed to a thimble or other symmetrical shape – think of a flat sandwich of components. In the sandwich, there is the Nernst electrolyte which is generally constructed from Yttria Stabalized Zirconia (YSZ), although other forms do exist. What is Yttria Stabilized Zirconia? It is Zirconia (ZrO_2) with roughly three percent of moles substituted with Yttria (Y_2O_3). Because every two zirconium ions are replaced with yttrium, an oxygen vacancy exists – this allows adjacent oxygen ions to "jump" to these sites and at elevated temperatures this activity is the basis for EMF production.

Continuing the discussion of the planar structure, there exists an internal "diffusion cavity" – this cavity is where the sample of exhaust gas is "trapped", as well as where the Nernst and pump sections face. How does the gas get there? By a diffusion process, the exhaust gas to be sampled enters the cavity. Not to get too "geeky" about the diffusion process, but suffice to say that there are two diffusion mechanisms: one is known as molecular diffusion, and the second is known as Knudsen diffusion, or "fine-pore" Very, very important to note: Knudsen diffusion is temperature dependent – this means that the porosity of the test chamber (i.e. how much gas can enter/exit) depends on the sensor head temperature – this is why pumping current (described next) is different for different temperatures, as well as exhaust backpressure dependence.

Now its pump-time! The aforementioned oxygen pump – this is what makes a run-of-the-mill oxygen sensor a true wideband unit – is really just another Nernst-type cell with an external current applied to it. So, we talked about the "cavity" above where sample exhaust gas exists and on one side is the Nernst measurement cell. On the other side is the pump cell – this cell is used to transport oxygen into and out of the measurement cavity. In very simplistic terms, if the exhaust gas in the measurement cell is lean, then there is excess oxygen (lean mixtures mean excess oxygen). We can "turn on the pump" to remove oxygen from the reference cavity – and with the proper feedback monitoring of the Nernst measurement cell we can pump out just enough oxygen to achieve a stoichiometric balance (roughly when the Nernst measurement cell reads 0.45 volts or thereabouts).

The best part of all: if we monitor the pump current, we can use this to determine lambda and AFR!

Pump current is related to the amount of oxygen pumped out as a function of time as:

$$n(\mathrm{O_2}) = \frac{i \cdot t}{4F}$$

with n being the moles of O2 gas pumped, t for time and current i. To make this equation useful it should be converted to partial pressure change within the reference cavity. Also note that the diffusion (explained before) will bring in more exhaust gas over time – so what we are doing is making an equilibrium with feedback from the Nernst measurement cell dictating how much oxygen to pump away, all the while more exhaust gas is diffusing in. Note that the pressure of the exhaust gas under measurement also affects the amount of diffusion into and out of the measurement cavity – this is the famous backpressure effect.

O.K. – we have explained the excess-oxygen case where the air-fuel mixture is lean. How does it operate on the oxygen-depleted side, or rich air/fuel ratio side? For this case, oxygen is 'pumped' into the measurement cavity simply by reverse application of current on the pump element. Feedback on the Nernst measurement cell indicates when stoichiometric equilibrium has been achieved.

Now, something should be bothering your gut right about now…

The pump cell operates on oxygen ion transport, but we are in a situation where there is no oxygen in the air-fuel mixture (i.e. we are rich). If we become much more rich, we still do not have oxygen. Super rich, and still no oxygen. How can there be a feedback situation in this case?

It turns out that within the diffusion measurement cavity, the following chemical reactions are occurring:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2$$

So, the oxygen pumping portion acts to introduce the oxygen into the diffusion chamber by the electrolysis decomposition of the carbon dioxide (CO_2) and water (H_2O) in the measuring gas. Think of it this way: we have exhaust gas trapped in the diffusion cavity which contains H_2 and CO, and the oxygen pump is generating O_2 – these combine to produce CO_2 and water. If we have more H_2 and CO in the exhaust gas, then more O_2 from the pump gets converted – and, in order to increase O_2 production we increase the pump current. And, it turns out that H_2 and CO are present in significant amounts for a rich AFR, and can be related to lambda by the elemental balance equation for the fuel/oxygenates/diluents we derived above.

Now, this is not exactly right, in that we are dealing with a gas balance and the pump is really an electrochemical cell (look up Le Châtelier's Principle in your chemistry book for equilibrium balance rules, as well as the ideal gas law), so we need the oxygen in the H_2O and CO_2 as donors for the reaction – this where the pump gets its oxygen. It's a balance, and by changing the amount of current pumped into the pump we can change the balance. The balance is also driven by the water-gas reaction, discussed later on.

Finally, lambda (what we all want) is related to all of the exhaust gas components in simplistic relation known as the Brettschneider equation:

$$\lambda = \frac{[CO_2]+\left[\frac{CO}{2}\right]+[O_2]+\left(\frac{H_{cv}}{4}\cdot\frac{K_p}{K_p+\frac{[CO]}{CO_2}}-\frac{Ocv}{2}\right)([CO_2]+[CO])}{\left(1+\frac{H_{cv}}{4}-\frac{O_{cv}}{2}\right)([CO_2]+[CO]+K1[HC])}$$

All this says is that there are known combinations of exhaust gas quantities (either in terms of moles or in partial pressure) that directly relate to lambda. These include H_2 and CO.

So, armed with all of this knowledge, we can write an equation relating pump current compared to exhaust gas component, then stick this into brettschneider (or a more advanced form – see the B&G paper). For the lean mixture side where there is excess oxygen, the pump current equation is:

$$I_p = K_{o2} \cdot \mathrm{P}_{o2}$$

So, the required pump current I_p is simply the partial pressure of O_2 in the diffusion chamber multiplied by a calibration coefficient K_{o2}. Remember, this is the partial pressure of oxygen, not the molar quantity, so the elemental mass needs to be involved.

For the rich mixture side, where there is no oxygen, the sensor measures the amount of CO and H2 in the exhaust gas (partial pressure):

$$I_p = -K_{co} \cdot \mathrm{P}_{co} - K_{H2} \cdot \mathrm{P}_{H2}$$

Note the minus signs – the applied pump current is reverse polarity such to make the oxygen pump an oxygen generator, not an oxygen sucker.

Also to note that on the rich side, the UEGO sensor reacts to unburned hydrocarbons as well. However, in a normal combustion, the amount of unburned hydrocarbons are in the parts per million region, whereas the moles of CO and H2 are substantially higher (like in the 10 – 20% range). If the influence of the unburned $H_\beta C_\alpha$ on the sensor is desired, then simply add (i.e. subtract) the partial pressure of $H_\beta C_\alpha$ times the corresponding diffusion constant.

Now, here is the million dollar question, and you only get chance: Where does one get the diffusion sensitivity coefficients K_{o2}, K_{co}, and K_{H2}?

A: You measure them with calibration gases.

And – the coefficients are different for each gas. One can determine K_{o2} by using a free air calibration, which has been corrected for elevation and barometer. The other coefficients require bench test gas setup.

There is much, much more to the whole wideband sensor operation, but the above should illustrate that there is a lot to consider in operating the sensor. Its easy to bolt a circuit together and get numbers out of it and call it correct, but it is much harder to understand the operation and compensate/correct for effects; so one should cast a critical eye on any number coming out of any wideband controller (including this one) until it has been proven accurate to some reasonable measure.

Q: Can you explain the overall circuit operation?

A: Sure! The heart of the system is the Motorola 56F8323 DSP/Controller. This is a 16-bit fixed-point DSP operating at 64 MIPs with a plethora of on-board peripherals, and it operates over the automotive temperature (-40 deg C to +120 deg C). The DSP has the usual collection of items like decoupling capacitors, crystals, etc. This DSP also has a JTAG emulator connection, allowing in-circuit board development. Core and I/O voltage is 3.3 volts. Other nifty items are an on-board 12-bit ADC, CAN, SCI, and SPI. And, there are free C compilers and debugger tools available for this device.

Next in line is the 4-channel DAC, the Linear Tech LTC1458. This DAC communicates to the DSP using a standard SPI interface. The four channels each are assigned a function: channel 1 controls the heater power supply, channel 2 controls the external wideband analog output, channel 3 is used for the UEGO pump drive, and channel 4 is used for setting up a variable reference for the return path of the Nernst/pump cells in the sensor. The DAC is a 5-volt device, but its logic 1 threshold is 2.5 volts, hence the DSP can drive the DAC to a logic 1 level using 3.3V. For the “other” direction (MISO), a pair of resistors form a voltage divider.

Next is the actual sensor control. For pump and virtual ground drive, a Linear Tech LT1639 is used for both its drive current capabilities (rail-to-rail) and its capability of driving large capacitive loads. For the actual pump current detection circuit, a precision instrumentation amplifier from Burr-Brown (now Texas Instruments), the INA114 is used. This device has a superior common-mode rejection ratio, something really required in a noisy environment. The output of the INA114 is presented to the ADC in the DSPTo measure the resistance of the Nernst cell (for heater regulation), a 3 KHz squarewave is coupled via. a capacitor, and its response is also capacitor-coupled and amplified, forming a synchronous rectifier. The actual DC level of the Nernst cell is buffered by an op-amp and introduced into the DSP.

The next part is the heater control. This is accomplished using a Linear Tech LT1170 switcher configured in a SEPIC topology. This switcher circuit is capable of providing up to 4 amps of continuous power, and the voltage is adjustable by the DSP from 5 to 16 volts – this range is independent of the vehicle’s electrical voltage.

The power supply consists of a Murata BNX002 noise filter on the power input. Due to low power consumption in the circuit, standard linear regulators are used for the 5.0 and 3.3 volt supplies. A precision voltage reference (REG113NA) is used to generate the mid-point voltage of 2.5 volts – this is also used as the reference of the ADC.

The input for the exhaust backpressure sensor is buffered by a National LMC6484 opamp. A complete thermocouple amplifier and cold-junction conpensation is provided by the Analog Devices AD595. The thermocouple is used to monitor exhaust temperature in order to determine the water-gas equilibrium.

The physical layer CAN transceiver is the Microchip MC2551, and there is a jumper-selectable termination resistor. The UART physical layer driver is the MAX3245, which can operate at up to 1 mbit/sec for extremely fast UART communication.

Q: Why did you use a DSP Hybrid instead of a Microcontroller?

This is a pretty easy question to answer – if one understands the operation of the wideband UEGO sensor (re-read the above section if it is not clear).

In the last few years, DSP hybrid microcontrollers have hit the market. Simply put, they combine the best features of a Digital Signal Processor (DSP) and Microcontroller. Best features include things like multiply-accumulate operations, extended precision math, bit operation, and good on-board peripheral sets. And the $$$ cost for these devices are very, very low.

Many manufacturers offer these devices, including Texas Instruments (TMS320C28x) and Microchip (dsPIC). Motorola has offered the DSP56F80x family for some years, and have just recently came out with the 56F83xx family – this is the device which was chosen for the Precision Wideband Controller. The on-board 12-bit ADC and the free compiler is enough to sway anybody, let alone the other rich mix of peripherals and on-board flash memory – and, by the way, 64 MIPS!

One could have used a simple 8-bit Microcontroller for this application, but after crunching thru all of the math (if one implements it) it would simply be taxed. The hybrid DSP is literally two dollars more, and has plenty of horsepower for the calculations. It's the 21st century – we have had enough of trying to squeeze code into 1K of memory and instituting massive lookup tables because the part cannot do a simple division without chewing massive clock cycles.

Q: Why take a mathematical approach in determining wideband output – why not just a simple lookup table?

Re-read the section under the operation of the wideband sensor, and re-read it until it sinks in.

The simple curve in the Bosch LSU-4 datasheet is for a specific hydrocarbon fuel, using test gas on a bench.

One can take this curve, stick it in their controller, and spit out the value based on pump current, and say it will work for all applications. Heck, why even bother sticking in this curve – just spew out any old number. No one will even know, and as long as they are getting numbers, they are happy. Ignorance is bliss, they say.

And, as the late Garfield Willis (of EGOR fame) expressed a few years back, "it's like playing AFR horseshoes with the blind!"

Q: Why such a complicated heater circuit?

Perhaps the most critical aspect of control of the wideband sensor lies in maintaining a known and constant sensor temperature. The transfer curve of the Nernst cell and oxygen pump operation is *very* temperature dependent. What this implies is that for a given pump current required (in order to maintain a balanced Nernst cell/oxygen pump equilibrium) will change as a function of temperature.

In order to maintain a valid calibration of Nernst response, either the cell must be maintained at a constant temperature or a calibration adjust which is a function of temperature be applied in order to correct for temperature offsets, or a combination of both. This is imperative if one wants to obtain consistent and comparable results over all operational conditions. Remember, any wideband circuit will give you a number, but in order for it to be consistent the operational temperature of the sensor head must be constant.

So, just turn on the heater and let it be! Its not that simple. Consider a few real-world scenarios:

Scenario #1: You need to merge onto a freeway and there is very short acceleration lane. So, you punch the pedal to the floor and the engine roars to a high RPM while you merge onto the freeway. During this time, there is an increase of exhaust gas flowing across the sensor head, both rate and temperature. So, the sensor will heat up during this time due to thermal transfer from the exhaust gas to the sensor. But, if the sensor heats up, then the Nernst response function will change, as will its transient response. So, we need to determine the temperature of the sensor head and correct the oxygen pump current readback.

Better yet, if the sensor's heater was throttled back during this time, then it is possible to maintain a small temperature deviation just by constantly monitoring the sensor temperature and adjusting the heater's applied voltage and/or current. Since the heater's impedance is for the most part constant during warmed-up operation, adjusting the voltage will in fact control the heat output (energy). So, one just simply reads the sensor temperature and if there is ever an increase in temperature throttle back the heater, and vice-versa.

A method used by many wideband controllers for control of the heater is by the use of Pulse-Width Modulation (PWM). What this does is quickly turn on and off the heater (at hundreds to thousands of times per second). The ratio of on-time to the overall PWM period determines the amount of average heat applied to the heater, and is usually expressed in percent. So, a 90% PWM means that the heater voltage will run at 90% of the current battery voltage. PWM waveforms are easy to geneate with a microprocessor - just feed a PWM signal to a transistor or FET switch and have this control the heater.

Problem solved. - Or, is it??? Consider the following:

Scenario #2: It has been snowing outside, and all of the roads are blocked with snow and ice. You are stuck in a very slow moving mass of traffic, just barely crawling. It's bitter cold outside, so you have the heater cranked up full blast. It's dark and hard to see so you have the headlights on. And the snow keeps on coming, so the windshield wipers are just flailing away at full bore. The engine is pretty much at idle as you crawl at a snail's pace. You really hate winter! And, so does your vehicle's electrical system…

While all this is going on, what do you think your vehicle's battery voltage is? If you are lucky it is in the 13 volt range or so, but bets are it may be running lower, like in the 11 to 12 volt range. Your alternator (with the engine at idle) is trying its best to keep the power needs of the wipers, headlights, heater motor, and to maintain a decent change on the battery, which may be quite low right now because you had to crank and crank a few minutes back due to the bitter cold temperature.

As you crawl along, you experience a few puddles of icy water muck which splash up under the vehicle - this hits the exhaust system at various places and cools the tubing and anything screwed into it (like a sensor) in nice extreme temperature jolts.

So, we have low battery voltage, an engine at idle not producing much exhaust flow (i.e. heat), and water splashing about causing all sorts of temperature gradients in the exhaust. We can clearly see that the sensor's heater voltage needs to be pretty maxed out in order to maintain a target operating temperature.

So, the PWM is cranked up by the microprocessor to maximum - 100%. But, we have a low vehicular voltage, in the 11 to 12 volt range, or less. If the heater PWM switch element is a FET, then it should only drop a few tenths of a volt (Rds of the FET) with the rest being applied to the heater. If the heater switch control element was something like a Darlington transistor (ie.e TIP120 or similar), then life is much worse, in that a saturated Darlington collector-emitter has a voltage drop of roughly 2 volts - this means that out of our 11 volts of battery, we just threw away 2 volts in the transistor as heat, leaving 9 volts for the heater. Sheesh!

One will find that the target operating voltage for the sensor like the LSU wideband is something around 10.0 - 11.5 volts (this is sensor specific). You can do the math.

Now, the question of the day: what if 100% duty cycle at our vehicular voltage is not enough to bring the heater up to temperature? If not then we have to run the sensor off of the desired temperature target. In this case, we had better make sure the temperature interpolation values for pump current is correct. [By the way, do you hear of any of the other wideband sensor controllers out there discuss pump current correction for off-temperature operation?]. Additionally, the Nernst response will also suffer.

Now, like in the movie "This is Spinal Tap", wouldn't it be nice if we could turn up the heater voltage, like they desired with their guitar amplifiers? With the Precision Wideband's heater circuit we can do exactly that, just like Spinal Tap's "When ten is not loud enough, we can turn our amps up to eleven".

The Precision Wideband uses a switch mode power supply to control the heater, using a topology known as SEPIC. This power supply is capable of maintaining the voltage at a specified voltage regardless of the vehicular voltage – even if the vehicle's voltage drops to a level of 7 volts, the heater will be maintained at the required higher voltage of 10 – 12 volts. The voltage is set by the DSP and is corrected in real time (i.e. at a rate of 100 times per second - real-time for the lag time of the heater) based on measured sensor temperature.

Q: What is a SEPIC Switcher?

The topology of the switchode power supply for the heater is known as SEPIC (single-ended primary inductance converter). The advantage of this topology over, say a buck-boost, is that the output is the same polarity as the input (a buck-boost inverts the output). Maintaining a positive reference with respect to ground makes functions like current measurement easier. The output voltage can be higher or lower than the input voltage, and in this circuit the voltage is set by the DSP (more below). Hence, the heater voltage can be set from a range of 6 volts to 16 volts and does not depend on the input voltage. With this, the heater can be controlled in a direct and repeatable manner.

Q: Why did you choose the LT1170 Switcher for the power supply?

A: Simple answer – it is pretty much a bulletproof device. It handles input power overvoltage situations to 40 volts, application of reverse battery, and the output can be shorted indefinitely without damage. Since the switcher can provide over 4 amps continuous, this is a good feature indeed!

There are a slew of other switchmode power supply drivers out there, and many will work equally well.

Q: How did you make the fixed-voltage LT1170 Switcher adjustable by the DSP?

A: It turns out that the LT1170, like many switchers, use a resistor divider to tap off of the output voltage, and use this as a feedback to adjust the output (voltage feedback). The junction of these two resistors want to be at 1.24 volts – if this junction is higher then the switcher adjust the PWM duty cycle to lower the output voltage, and vice-versa. The resistors values chosen yield approximately 12 volts in the switcher output.

Now, if one introduces a current in this junction, they can alter the steady-state point. This is done with one of the DAC channels and a series resistance. Now, by adjusting the DAC voltage, the steady-state point will be moved and the switcher will then compensate by either increasing or decreasing the output.

This setup works exceedingly well. Heater voltage response to DAC setpoint changes are well within the bandwidth required for real-time heater control.

Q: What is the LTC1458 DAC, and can you explain its function?

A: The LTC1458 is a four-channel, 12-bit Digital-to-analog converter, also known as a DAC. Its purpose is to provide analog voltages as are commanded by the DSP. The DAC is used to generate the analog wideband signal, heater power supply voltage adjustment, and UEGO pump and reference control.

Now, this part is not the most inexpensive DAC out there, but its capabilities outweigh its cost, items like a built-in reference, different target ranges, and a very fast SPI interface make this a really nice device.

Now, it is possible to use a timer channel running in a PWM (Pulse-Width Modulation) mode and use external low-pass filtering to achieve a digital-to-analog converter. And the DSP has 6 PWM channels that can operate at very high speed. But, there is always a small amount of ripple, unless the low-pass filter is pretty sharp, then the problem becomes a lag in response due to all of the filtering. A DAC is pretty much instantaneous in its response to a new setpoint, and we have a really fast computation engine within the DSP, so the added cost is well worth the expense.

Q: Explain the Nernst and pump feedback setup.

A: The operation of the UEGO sensor basically requires reading the instantaneous Nernst generated voltage, and providing oxygen pump current which will bring the Nernst cell voltage to a target value (around 0.45 volts). Many systems employ an analog system that adjusts the pump current in a feedback loop. Often, a PID (Proportional-Integral-Differential) control loop is used, with the proportional part relating to how far off the Nernst cell voltage is from the target 0.45 volts, the integral part is used to compensate for the lag and the offset in the pump cell, and the differential part used to control the ramping of the pump based on the rate of change of Nernst response.

An analog solution works well, but it is "tuned" for a particular response of a sensor. Different sensor manufacturers have different feedback response (transfer function), so to change sensor head type would require hardware PID loop changes.

Another implementation method is to provide digital pump control, where the analog voltage of the Nernst cell is digitized and manipulated in software, and a reverse operation (DAC) used to control the pump voltage (and hence current).

Using software to maintain the feedback loop opens up an exciting chance to experiment with different control algorithms. Since this is an experimental wideband controller, making the loops in software will allow the implementation of different feedback techniques. A few that come to mind are:

- Simple brute-force pump current control based on Nernst cell voltage. This could be implemented in simple code, or as a lookup table of pump current setpoints compared to Nernst voltage.
- Digital PID loop. It is really easy to implement a digital form of a PID loop, where all of the parameters are adjustable in software. And with a DSP it is really easy to implement a recursive version of a PID loop:

$$Y_i = Y_{i-1} + A_i e_i + A_2 e_{i-1} + A_3 e_{i-2}$$

$$A_1 = K_p + K_i \frac{\Delta t}{2} + \frac{K_d}{\Delta t}$$

$$A_2 = -K_p + K_i \frac{\Delta t}{2} - 2\frac{K_d}{\Delta t}$$

$$A_3 = \frac{K_d}{\Delta t}$$

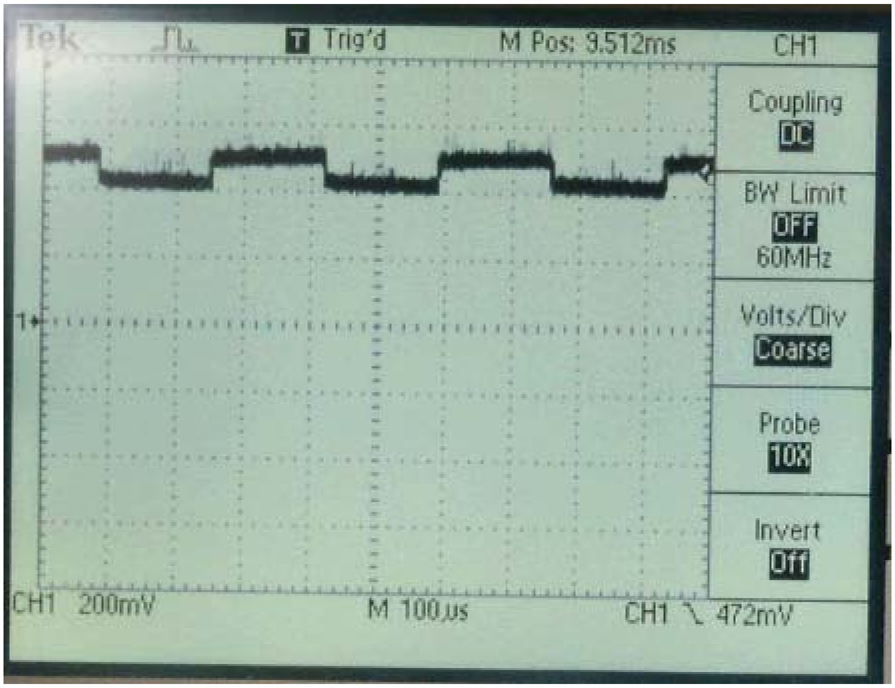
  Y_i = Current pump voltage output,
  Y_{i-1} = Previous pump voltage,
  e_i = Current error of Nernst cell reading from the target 0.45 volts,
  K_p = Proportional PID term,
  K_i = Integral PID term,
  K_d = Derivative term.

  This form of the PID control loop is optimum for a DSP, which is designed to perform multiply/accumulate operations in a single clock cycle. Also note that the terms A_1, A_2, and A_3 are generated only once (unless the PID parameters change), so the only real calculation is the recursive relation with Y_i.
- Exotic filter implementations, like a predictor-corrector structure, Least-Mean-Square, or Kalman filter. We have the horsepower for implementation of any of these.

So, those who like to experiment prepare to have some real fun – we have fast hardware and a computation engine that we can really do anything from the simple to the ultra-complex. And learn something in the process.

Q: How is the Nernst cell's resistance measured?

A: Using a 3-KHz squarewave superimposed on the Nernst cell with a fixed amplitude, the resulting level of this waveform can be used to determine internal resistance using Ohm's law. More on this is in the next section, but here is what the waveform looks like:



Q: Why is measuring the Nernst cell's resistance so important?

Accurate temperature control of the wideband UEGO probe is an absolute requirement during operation. Changes in UEGO probe temperature will result in a change in required pump current (from the difference in diffusion in and out of the measurement cavity), so monitoring the temperature allow for corrections to be applied to the measurements. The LSU probe does not have any form of direct temperature measurement (i.e. thermistor, etc.). However, monitoring the resistance of the reference cell yields a close representation of the probe temperature - the resistance of the reference cell varies with temperature. The Nernst reference cell has a high resistance at low temperatures (i.e. ambient temperatures) and a resistance of approximately 80-100 ohms at normal operating temperature. So, by monitoring the internal resistance of the reference cell it is possible to determine an accurate UEGO probe temperature, without the need of an external temperature sensor element.

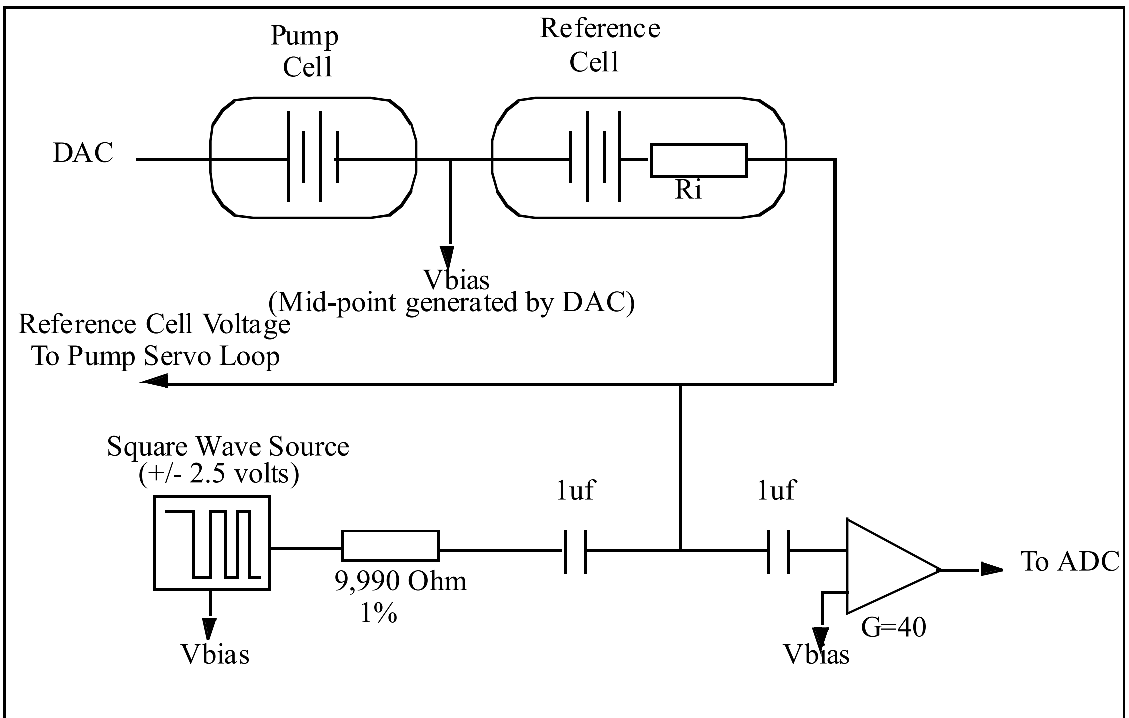
There are several methods available to measure the resistance of the reference cell, including disabling the pump circuit and applying a known constant current across the reference cell and measuring the resultant voltage, finally re-enabling the pump circuit. This method requires several analog switches to apply the current and re-establish the pump servo circuit when done. Also, if a bias is applied to the Nernst cell, then an opposite polarity current with the same duration needs to be applied in order to "reset" the polarization on the cell. The one problem with this method is that it is "intrusive" to the feedback loop of the Nernst/pump.

Another method is to apply a high-frequency waveform to the pump circuit and measure the resultant deviation in EMF. The reference cell's resistance is determined by AC-coupling a square wave of known amplitude and frequency via a series resistance, and measuring the resultant AC waveform's amplitude. This waveform is always present, and since it is at a high frequency with respect to the response of the Nernst/pump feedback loop, it essentially averages out. This is the method employed in the PWB.

Circuit operation is very simple. A known square-wave source of 5 volts peak-to-peak and at a frequency of 1 to 3 KHz (generated by the DSP) is capacitively coupled to the reference cell positive terminal. Overall current is limited by a series resistance (plus Ri internal resistance) to 500 microamps peak to peak, or +/- 250 microamps around the Vbias point (Vbias is set to 2.5 volts to allow for bi-polar pump operation) - this value meets the specification outlined in the Bosch LSU 4.2 data sheet. The alternating current signal generates a corresponding alternating voltage with value based on the internal resistance Ri. For example, if Ri = 100 ohms, then 500 microamps (P-P) multiplied by 100 ohms yields 50 millivolts p-p, or +/- 25 mv around the Vbias point. Actually, the series current limit resistance and Ri form a resistor divider circuit driven by a voltage potential.

To measure the voltage, a capacitor is used to block the DC offset (i.e. reference cell voltage) and pass the alternating signal. A gain stage is introduced and the voltage is fed into a A/D port on a processor. Note that this signal is an AC signal, so ADC sampling needs to correlate with the polarity of applied square wave signal – this is known as synchronous rectification. An alternative method would be to use a bridge rectifier circuit to recover the positive/negative swings and then filter before application to the ADC channel.

A picture is worth a ton of words:



Ri Determination via AC Signal

Q: Explain the pump control circuit – why use two DACs?

A: The general implementation of the pump circuit is to simply bias the pump/Nernst return to a mid-point voltage. For example, for a circuit using 5 volts for full swing, a mid-point bias of 2.5 volts or thereabouts is often used – this mid-point bias is applied to the Nernst/pump return. Therefore, the pump control voltage (feedback) can range to a theoretical -2.5V to + 2.5 volts (if the bias is chosen to be 2.5 volts). This control voltage generates a current flow in the pump.

Lets take a look at the equation for pump voltage around the loop:

$$V_{pump\_loop\_voltage} = \left|[(R_{sense} + R_{series}) * I_{pump}] + V_p\right|$$

Where:
R_{sense} is the sense resistor for detecting pump current,
R_{series} is all other series resistances in the pump loop. For instance, small values of series resistance is often added to unity-gain op-amp drives (i.e. wide bandwidth op-amps) in order to prevent oscillation,
I_{pump} = Pump current,
V_p = "Polarizing Voltage" of the pump cell – this is a voltage needed to polarize the pump cell in order to source or sink oxygen. Nominal values for V_p are +450 mV for oxygen sink and –350 mV for oxygen source.

So, the pump drive has to first overcome the polarization effect of the pump cell, then its current will be dictated by the series resistance and the applied pump potential ($V_{pump\_loop\_voltage}$). Using extreme values for R_{sense} and R_{series}, and the fact that op-amps typically do not drive at full current when they are very close to the supply rails (i.e. V_{sat} saturation voltage, typically around 100 to 200 mV depending on op-amp operating temperature and type.) one can determine "comfortable" values of pump current of +/- 10 mA. This range is sufficient for many applications – however, for boosted operation (i.e. turbo/supercharger applications) the (possible) increased exhaust backpressure leads to a decrease in sensor response – this implies that more pump current is needed to achieve the same sensor reading.

In order to ensure that sufficient pump current is available for all operating conditions and sensor applications, the voltage of the mid-point (Nernst/pump return) is set by a voltage DAC (Digital-to-Analog Converter). The pump voltage terminal is driven by another DAC channel. So, with this arrangement, it is possible to apply close to +/- 5 volts across the pump – but in practical setups a range of +/- 4 volts is possible.

Note that the +/- 4 volt range can be obtained by using a 8-volt source and a 4-volt mid-point bias (like in the DIY-WB circuit). But, by using two DACs under software control, the same range can be achieved with only a 5 volt supply.

In addition, having a "moveable" mid-point reference has an additional benefit. For measuring pump current, the voltage across resistor R_{sense} is detected by the INA114 instrumentation amplifier. It is a well known fact that best common-mode rejection is obtained when the input bias currents are very close – this occurs when the voltage difference across the R_{sense} resistor is equidistant to the instrumentation amplifier mid-point potential (think symmetry in the circuit). In this circuit, the mid-point potential for the INA114 is 2.5 volts – so it is desirable to adjust the two DAC values such that the actual voltage on one side of R_{sense} and the other side of R_{sense} are the same delta from the 2.5 volt bias.

Q: Why use the INA114 Instrumentation Amplifier – why so complicated?

A: It turns out that this device makes the system **simpler** and much more **accurate**. The common form of measuring the pump current of the UEGO sensor is to place a known resistance in series with the current flow and detect the voltage drop across this resistor. A common method of detecting the voltage difference is to use an op-amp configured as a differential amplifier, with the output being the difference between the two input voltages multiplied by a gain.

What we are after is a difference measurement between the voltage present on the current sense resistor. The issue here is that we want to measure the difference without any influence on the actual voltages. This leads to the parameter common-mode rejection ratio (CMRR). This is a measure of how well the amplifier rejects common voltages compared to the differential voltage – usually in units of dB. Larger CMRR values means that common-mode voltages have less influence on the measurement of differential voltage.

A typical op-amp (like a LMC6484 or equivalent) has a CMRR value of 60 dB at a gain of 1. The INA114 instrumentation amplifier has a CMRR of 96 dB at a gain of 1 typical.

Additionally, an instrumentation amplifier configuration utilizes two unity-gain op-amps as buffers to the input terminals – this increases input impedance and decreases bias current effects as compared to the traditional 4-resistor differential amplifier configuration.

The INA114BU is very easy to use. Just one resistor is used to set the gain. With a traditional differential amplifier topology, four resistor are required and these resistors need to be matched to 1 percent or better – or the result is unequal bias currents and resultant measurement error. This matching needs to be the same for all temperatures – unequal heating can cause the tolerance to drift.

Simply put, the INA114BU defines the word “Precision” in the Precision Wideband Controller. This is a very critical component of the controller, and its price is well worth the accuracy.

Q: Why are you not using the calibration resistor contained in the sensor?

A: Most of the UEGO sensors, most notably the NGK and Bosch, include a calibration resistor in the wiring harness. The resistor is used in OEM applications for determining calibration, such that the sensor can be installed in mass production without interaction.

The “problem” with the resistor lies mainly in the fact that it is buried in the wiring connector, so the mating connector is a requirement in order to use calibration resistor. With all of the different target vehicles in use using the UEGO sensor, the result is a plethora of connector version, and all are unique. In addition, in the configuration used by Bosch, the calibration resistor is connected in parallel to a known internal resistor (61.9 ohms), forming a new resistance in the 30 to 100 ohm range. This resistance is used to determine pump current in a differential amplifier mode. But, since the resistor is buried in the connector harness, and aging of the resistance will change the calibration. In addition, with the extra wiring to include the resistor into the circuit, there is more chance of inducing common-mode noise.

In order to eliminate the requirement for a mating connector for the particular sensor in use, we chose instead to use a fixed pump current measurement resistor (61.9 ohms). Using this known value, and using a free air measurement (that has been corrected for altitude/vapor pressure effects) the conversion required from pump current to lambda can be determined in software. For the rich side, representative numbers can be used (scaled by this measurement), but (of course) the best method is to determine the diffusion coefficients for CO, H_2, and HC by the use of known gas standards on a measurement test bench.

Q: The power supply section seems complicated – why?

A: The power supply is really very simple. The +12V battery comes in on signal **12VRAW** thru a SMT fuse and engine ground is on signal **12VRET**. This is introduced into a noise filter BNX002 (Murata), eliminating the majority of vehicle noise and spikes. It also keeps out the high-frequency switcher noise generated by the heater power supply from contaminating the vehicle supply. The **12V_CLEAN** is the signal line to the heater switcher supply – it is not reverse protected because the switcher power supply already has reverse polarity protection. The **12V_THERM** signal is the power supply for the thermocouple amplifier.

There is a 5-volt regulator of the standard LM2940 type. The diode across the output to the input of the LM2940 provides protection to the regulator in case the input supply suddenly drops off. From here the 5-volt output is protected by a Polyfuse fuse. The fuse is a resettable type, and provides protection for pretty much the entire circuit (including the other voltages). The 5 volts is regulated to 3.3V for the supply for the DSP core.

In addition, a precision 2.5 volt reference supply is provided by the REG113NA-2.5 regulator. This is a special regulator that possesses very low noise characteristics and very high stability – and we need both. This is used for both the mid-point bias voltages for the 5-volt op-amp circuits and the reference high voltage supply for the ADC.

Q: Why is there a Thermocouple Amp in the circuit?

A: The use of the thermocouple is used to detect the temperature of the exhaust gas. But, the reason is not to monitor the temperature for optimum mixture tuning. It turns out that to determine the gas composition of the exhaust requires knowledge of the exhaust gas temperature.

Using an analytical method for determining Lambda/AFR from generating a molecular balance of known intake hydrocarbon(s) (see the B&G paper on analytical lambda/AFR calculations), the numerical value of a ratio known as the "Water-Gas Equilibrium" is desired. The formulation of the water-gas equilibrium is the following:

$$K_p(t) = \frac{\mathrm{P}_{CO} * \mathrm{P}_{H2O}}{\mathrm{P}_{CO2} * \mathrm{P}_{H2}}$$

where:

P_{CO} is the partial pressure of CO,
P_{H2O} is the partial pressure of H2O,
P_{CO2} is the partial pressure of CO2,
P_{H2} is the partial pressure of H2,
$K_P(T)$ is the water-gas equilibrium constant, which is a function of exhaust gas temperature.

So, the value of K_p varies with exhaust gas temperature (for example, at 1700 degrees C the value of K_p is roughly 3.3) – this determines the ratio of partial pressures of CO, H2O, CO2, and H2. And, since the wideband lambda sensor is sensitive to *both* the partial pressure of CO *and* the partial pressure of H2 (with different sensitivities), it is required to know the ratios of the partial pressure of these two gases in order to compute lambda.

Note that the water-gas equilibrium is needed only for an oxygen-depleted mixture situation (i.e. a "rich" condition).
It is easy to generate the quantity (moles) of both CO and H2 based on a given hydrocarbon composition, lambda, and water-gas equilibrium ratio. For example, for a lambda value of 0.5 and hydrocarbon ratio of 1.85 for H/C and 0 for O/C (unleaded pump gas) a table can be generated of CO and H2 mole percentages vs. lambda for various water-gas equilibrium values (values can be verified by the use of Brettschneider):

Water-Gas Equilibrium Temperature (Kp value)	Percent Moles of CO	Percent Moles of H2
1700 (3.34)	18.3	12.8
1550 (2.75)	18.0	13.1
1350 (1.95)	17.5	13.8
1150 (1.19)	16.6	14.7
950 (0.57)	15.2	16.1
750 (0.16)	13.3	18.0

Similar tables can be generated for other lambda values (less than 1.0). Also note that the table above lists the moles of each gas – the lambda sensor operates on partial pressure, so the quantities above need to be converted to molecular mass for all of gas constituents.

Do not confuse the exhaust temperature with the sensor heater temperature – even though close regulation of sensor head temperature is occurring, the actual temperature of the exhaust gas can be different. So, to measure the water-gas equilibrium, a thermocouple is mounted nearby the wideband UEGO sensor head. The controller supports the use of a K-type thermocouple, which are widely available.

Finally, the Precision Wideband Controller will operate without an external thermocouple, but there will not be a correction of the water-gas equilibrium. For many applications this may be an acceptable situation. But, for applications requiring high repeatability, the fitting of a thermocouple should be considered, as is the monitoring of exhaust backpressure.

Q: Why did you choose the AD595 Thermocouple Amplifier?

A: The AD595 thermocouple amplifier, made by Analog Devices, incorporates cold-junction compensation for K-type thermocouples. Thermocouples are relative measurement devices, so a known reference is needed in order to obtain absolute temperatures. A "cold-junction" is normally used – it can be a literal thermocouple at a temperature of 0 degrees C, or more practically a synthesized reference (i.e. current) which simulates the cold junction.

Q: Where is the Analog-to-Digital Converter, and what is its resolution?

A: This one is simple – it is a 12-bit ADC integrated within the 56F8323 DSP.

It should be noted that Motorola has employed significant design emphasis to the integrated linearity of the ADC, to the point that they bring out the mid-point reference of the ADC in order for external compensation (i.e. capacitor).

Q: What is a CAN Physical Layer and why do we need it?

A: CAN, or Controller-Area-Network, is a serial networking protocol which was designed by Bosch for use in automotive environments. CAN offers a robust and easy to use networking infrastructure.

Why does the Precision Wideband Controller need a network like CAN? In the implementation of the controller, the use of an analytical method of determination of lambda means that it is possible to let the controller know if there is a change in hydrocarbon. For example, when injecting nitrous, the chemical balance with respect to the hydrocarbon ratios are altered – this will lead to inaccurate calculation of lambda unless it is accounted for. The integration of UMS will provide information back to the Precision Wideband Controller (using CAN) on any hydrocarbon change, in real-time. So, if UMS knows that nitrous (for example) has been introduced, it can send a CAN message frame to the Precision Wideband Controller on this fact, which can account for the change in hydrocarbon ratios in the calculation of lambda. Same goes for water injection – this changes the hydrocarbon ratio by displacement and chemical combination in the combustion process.

This is yet another example of the difference between a wideband meter and a real-time mixture controller!

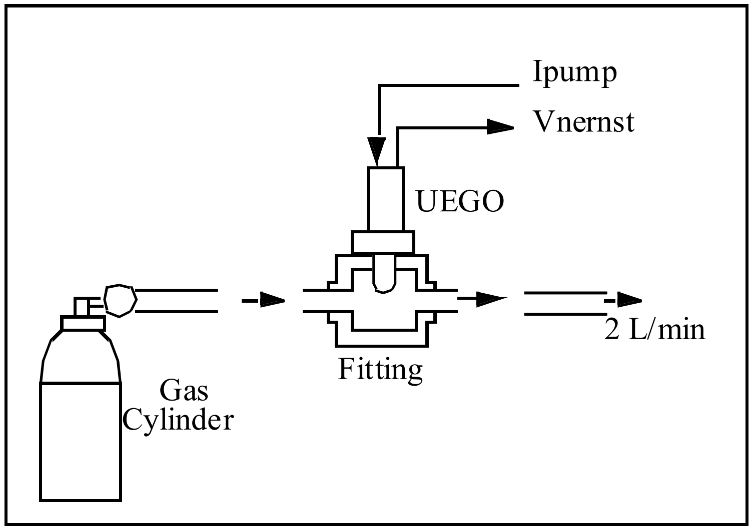
Q: Explain the Serial UART Interface – anything special here?

A: Of course there is -:) The physical layer chip can run at speeds in excess of 1 mbit/sec! So, very high speed serial datalogging to external computers (i.e. PC) is now possible.

Q: In general, how does one calibrate a wideband sensor?

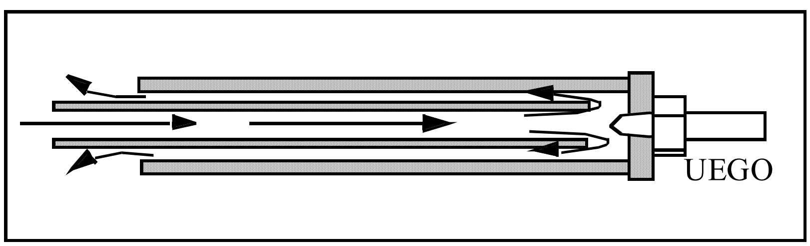
A: Calibration of the wideband UEGO sensors is pretty easy, but it requires a known precision gas of certain mixtures. You will want a gas mixture for the lean, rich, and stoichiometric measurement.

The actual flow bench is pretty simple to build – just squirt some test gas over the sensor as shown in the following illustration:



There really is not much more to it than this. Obtain a mixture of test gas and regulate down to a flow of approximately 2 liters per minute. Using a tee fitting arrangement, pass the gas over the sensor. Set the pump current such to make the Nernst cell voltage 0.45 volts – this current corresponds to the diffusion constant for the partial pressure of gas in the cylinder.

An alternative fitting arrangement for the "tee" is an "end-tube" sort of arrangement:



Either sensor flow mounting method works for determining the coefficients.

Now for the gas mixtures. For the lean side, it is very easy. You can use atmospheric air (with the partial pressure of oxygen corrected by barometer/humidity/altitude), or even supply it with a small air compressor set to yield the 2 l/m flow.

For the stoichiometric point, nitrogen at a concentration of at least 99.999% is used. In order to provide oxygen donors to the mix, either mix in 2% or so of CO_2, or pass the N_2 gas thru a "washing bottle", which is just a flask or similar with distilled water where the N_2 gas has to bubble through – this will introduce water vapor in the mix.

For the rich side, the sensor reacts to CO, H_2, and H_bC_α. We need to test the sensor for each of these gas species in order to obtain the diffusion coefficient. All of these gases can be nasty to work with and pose a significant oxygen deficiency hazard, so be sure there is ventilation for the escaping gas. The mixtures can also explode - they are extremely flammable. You may want to keep a self-contained breathing apparatus setup around in case it is needed in emergency. We have warned you, and have included the "bad" symbol to back it up:

For the mixtures, pick a percent mix (by weight) that is roughly 5 – 10% of CO or H_2, and fill the remainder with N_2. You will also need a washing bottle or other means of introducing a few percent of H_2O or CO_2 like before.

For the hydrocarbon $H_\beta C_\alpha$, it gets a little tougher. One can flow Propane (of good quality) to get a feel for the magnitude of the coefficient. As before you will need a washing bottle.

For the gas mixtures, try to obtain Primary Gas standards, which are plus/minus 1 percent relative or plus/minus 0.002 percent absolute. Primary gas is "traceable to NIST standards" and will indicate this on the bottle. If this becomes too expensive, then a Certified Gas standard can be used in place. Expect to pay several hundred dollars for all of the gas mixtures – it is not cheap.

There exists a low-cost alternative, which may help in testing sensor heads – and we all like inexpensive solutions. Centers which measure vehicle exhaust gas emissions utilize 5 and 6-gas analyzers equipment. These setups require frequent re-calibration (on order of every half hour or so, depending on the testing apparatus). So, there are BAR-certified gas blends available that are used to calibrate the gas analyzers. These gas blends, which are 2% relative accurate, are manufactured in cylinders from BAR-certified gas blenders. These cylinders are pretty much the same – 12.74 liters of blend gas at 300 psi in a non-refillable (i.e. throw-it-away) cylinder with a valve with a 45-degree flare fitting. Note: these cylinders will require a regulator or some sort of orfice (like a Whitey or Nupro metering valve) so that you do not blow yourself up with 300 psi of gas pressure. Do not use without a regulating or restrictive device, period. Once again, the "bad" symbol:

There are different BAR-certified gas blends available – here is a table of the different blends:

Gas Species	BAR-90 mid	BAR-97 high	BAR-90 low	BAR-97 low	Units of measure
Propane (HC)	1200	3200	300	200	Ppm
CO	4.00	8.00	1.00	0.50	Percent Weight
CO2	12.00	12.00	6.00	6.00	Percent Weight
NO	0	3000	0	300	Ppm
O2	0	0	0	0	Percent Weight

The problems of using BAR gas blends is that none of them have a H_2 component, and all of them have both a hydrocarbon and a CO species – the sensor reacts to all of these. You are out of luck on the H_2 sensitivity, but by using two (or more) BAR blends it may be possible to set up a series of equations of pump current compared to the BAR gas mix and solve for the unknown coefficients.

BAR gas blends are available from http://partsqueen.com and other sources – price is around $30.00 a bottle.

Finally, for calibrating the lean side of things, i.e. the excess oxygen situation, one can use free air. That is use air at atmospheric pressure. Atmospheric air at sea level has roughly 21 percent oxygen (partial pressure) so this can be used for calibration. However, altitude and vapor pressure will affect the partial pressure component, so these need to be accounted for in the calibration. B&G has developed a Windows application that computes the required correction such that one can use atmospheric oxygen readings for calibration. Here is the link for the application and the documentation:

www.bgsoflex.com/partialp/partialp.zip

Dedication: We dedicate the Precision Wideband Controller to the memory of Garfield Willis. Garfield was instrumental in early research and development of the EGOR wideband controller.