Exhaust Gas Temperature Monitor For An Internal Combustion Engine

ELEC 399

FINAL REPORT

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Submitted on December 3rd, 2012

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1 Introduction

1.1 Objective

The objective of this project is to design a system to monitor and display the exhaust gas temperature (EGT) of an internal combustion engine. The system will be used by the UVic Formula SAE team to monitor the temperature of the exhaust gas in their car's engine with hopes that the data can give insight to the performance of the engine. It is possible that this data can result in better engine tuning and better overall performance of the engine.

1.2 Exhaust Gas Temperature

The ability to measure the EGT's of each cylinder in an internal combustion engine can provide useful data when it comes to engine tuning. The EGT can provide insight on the cylinder's air-fuel ratio (AFR), which is an important characteristic when it comes to performance. If not enough fuel is injected into the cylinders during the combustion process, the exhaust gas will be much hotter. This is known as a "lean" air-fuel ratio. Conversely, if there is too much fuel in the combustion process, the exhaust gas will be cooler. This is known as a "rich" air fuel ratio. An air-fuel ratio that is too lean or too rich can result in loss of performance in the cylinder. Additionally, if the air-fuel ratio varies significantly between each cylinder, then the fuel injection process is not distributing fuel evenly, resulting lower performance of the engine.

By monitoring EGT, the engine can be tuned in such a way to optimize engine performance.

1.3 Engine Tuning

When tuning the engine we monitor the engine using a Dynamometer (dyno). The combination of the dyno and the car's Engine Control Unit (ECU) allows us to monitor several engine characteristics simultaneously. The ECU used is called Megasquirt3 (MS3) and will be briefly described later in this report. The characteristics observed are gathered from various sensors throughout the vehicle and output to a Software platform offered by Megasquirt3 (MS3). During one engine test, it is possible to simultaneously observe the following vs time:

- Manifold Air Temperature (MAT)

- Manifold Air Pressure (MAP)

- Coolant Temperature (CLT)

- Throttle Position (TPS)

- Air to Fuel Ratio (AFR)

- Revolutions Per Minute (RPM)

- Horsepower (HP)

- Torque (TRQ)

Each of these characteristics provides insight into how the engine is performing. With this data we can tune the engine with the MS3. There are 3 things we can adjust:

- Spark Timing,

- Injector Timing

- Volumetric Efficiency (Volumetric efficiency is a ratio of the quantity of fuel and air mixture that enters a cylinder during the intake stroke to the actual capacity of the cylinder in static conditions.)

It is our hope that by adding EGT to the list of measurable characteristics, the engine can be tuned even more effectively then it already is.

1.4 EGT Monitoring System

In order to achieve effective EGT monitoring, our system will need to consist of:

1. Temperature sensors to be placed in the exhaust manifold.
2. Signal amplifier used to amplify the analog temperature signal
3. Data logging/displaying system to display the data.

There are several factors to consider with each of these components. This report will discuss our design in detail and provide information on future plans for this project.

2 Design

2.1 Temperature Sensor

When selecting a sensing method for the EGT, a number of factors needed to be taken into consideration. The temperature inside the exhaust manifold can range from 600-1200 degrees Celsius. The sensor would need to be accurate within this range, and also be able to withstand these high temperatures for an extended period of time without deteriorating. The formula SAE racecar is also prone to experience high g forces during it's operation, whether from normal track usage or potential crashes, vibrations, etc. The ideal sensor would need to be durable enough so that the probability of failure under these circumstances is very low. Also, the sensor would need to be small enough so that it does not significantly disrupt air flow through the exhaust manifold, which could hinder performance. Other factors to consider include price, ease of mounting, margins of error in measurements, and voltage difference per degree.

With these considerations in mind, we came to the conclusion that a K-type thermocouple would be the ideal sensor to use for this project. A thermocouple is made from two different conductors that are joined together and produces a voltage near the point of contact. This voltage is dependent on the difference of temperature of the junction in comparison to other areas of the conductors, and can be used to measure temperature. Since thermocouples are simply made of two different conducting wires, they are extremely durable and small enough so that the exhaust flow will not be disrupted. They also allow for a wide temperature sensing range, from -200 to 1260 degrees Celsius, a fast response time, and relatively low initial cost. The main downfall of a thermocouple is that the error can be relatively high, generally around 0.75%. The alternatives, however, also have limitations. Thermistors do not generally allow for a high enough temperature range, and although RTD's will work, and are more accurate, they are costly, less durable, and have a narrower temperature range. Since typical variations of temperature between cylinders are around 38 degrees Celsius, an error of 0.75% would still give meaningful results, and by taking the average of multiple measurements, the error can be significantly reduced.

A type K thermocouple uses the nickel-based alloys Chromel and Constantan for the conductors. It is durable and has good corrosion resistance due to being nickel based, making it ideal for use in an engine. It is also cost effective, and is the most common thermocouple available. Type K thermocouples typically have a temperature range from -200 to 1260 degrees Celsius, well within our required range, are cheaper than some of the alternatives, and have a reasonable tolerance within our intended range. It has an exponentially increasing thermoelectric voltage, making the difference in voltages easier to measure and more accurate at higher temperatures. This is ideal since it will normally be operating at higher temperatures. In the range from 293 degrees to 1250 degrees Celsius, the tolerance is +/- 0.75%. The graph below shows the voltage output as a function of temperature for a variety of thermocouples.

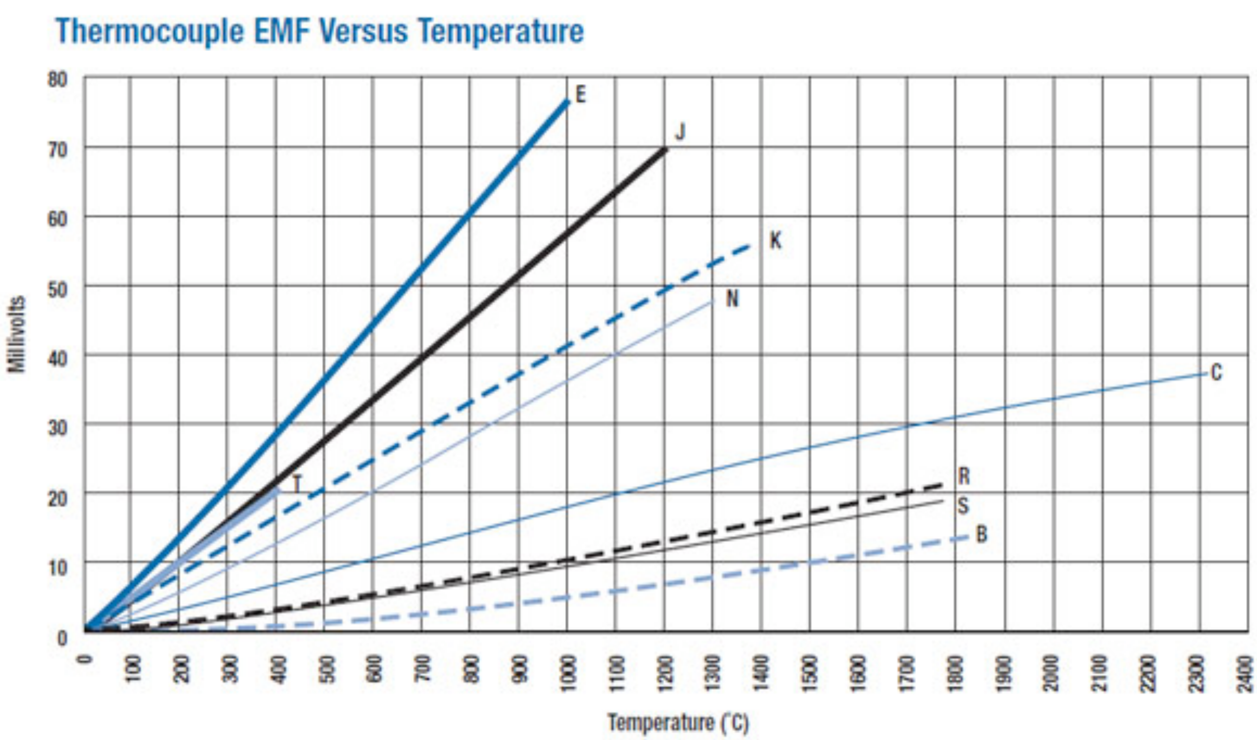


Figure 1 - Voltage vs temperature dependence for a range of different thermocouples.

Our choice to use a type-K thermocouple was solidified by the fact that, for measuring automotive EGT, type K thermocouples are generally the industry standard sensing mechanism. Because of this we know it is proven to be effective, and there is more information available on measuring EGT with these sensors than any other type. When browsing for a specific product to use we found a cost effective kit that includes four Stinger Hyper Response EGT probes, an amplifier, and mounting hardware. The price of the kit is $399.95, and is not much more expensive than purchasing the sensors separately. One advantage of using a kit is that the components are preselected to work properly together. For example, when connecting a thermocouple to any type of instrument, the connector has to be made of the same alloy as the thermocouple otherwise there will be an error in the measurement. This kit takes this into consideration and comes with compensated connectors to match the alloy used in the sensors. The sensors are high quality with all the required specifications, and since mounting hardware is included, installing the sensors and amplifier will be easier. We believe the finished product will be less prone to errors if we use a kit as opposed to mismatched products, or designing our own amplifier and mounting hardware.

Specifications of sensing capabilities:

- Exposed tip design allows for very fast response time of 0.6 seconds.
- Temperature measurement range is between 0 – 1250 degrees Celsius.
- Sensitivity of 41 microvolts per degree C. This becomes 4 mV per degree C with amplification.
- 72” wire length.
- Positive leg is non-magnetic (Yellow), negative leg is magnetic (Red).
- Appropriate for use in oxidizing or inert atmospheres at temperatures up to 1260°C.

Below is a graph of the output voltage of a similar type K thermocouple vs temperature, as well as a graph depicting the deviation from the straight line approximation at any given temperature. From these graphs we see that in our intended range, from 600 to 12000 degrees C, the output voltage vs temperature is approximately linear, with a maximum deviation of about +/- 10 degrees C. Using information from these graphs we may be able to better calibrate the sensors.

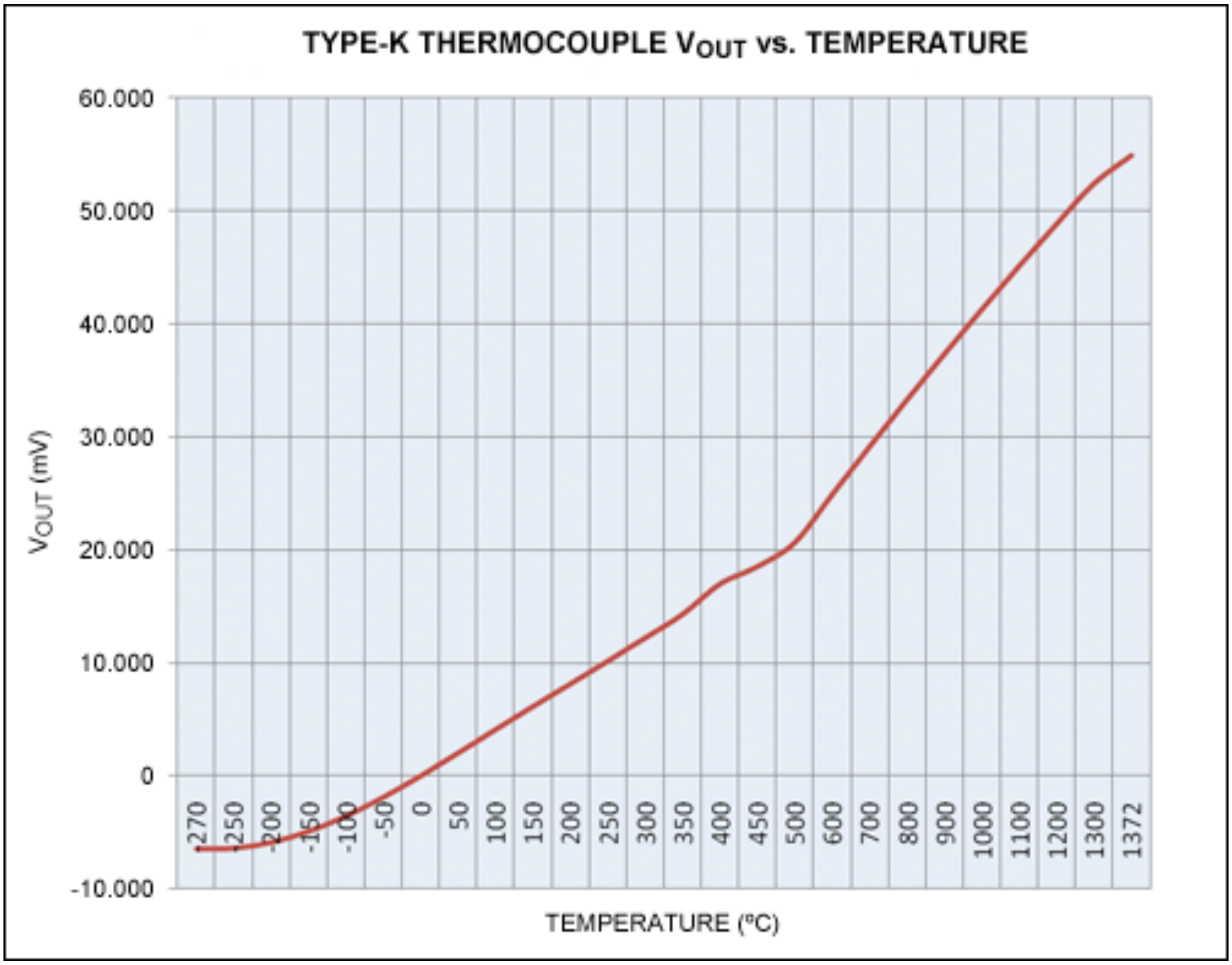


Figure 2 - K type thermocouple output voltage as a function of temperature

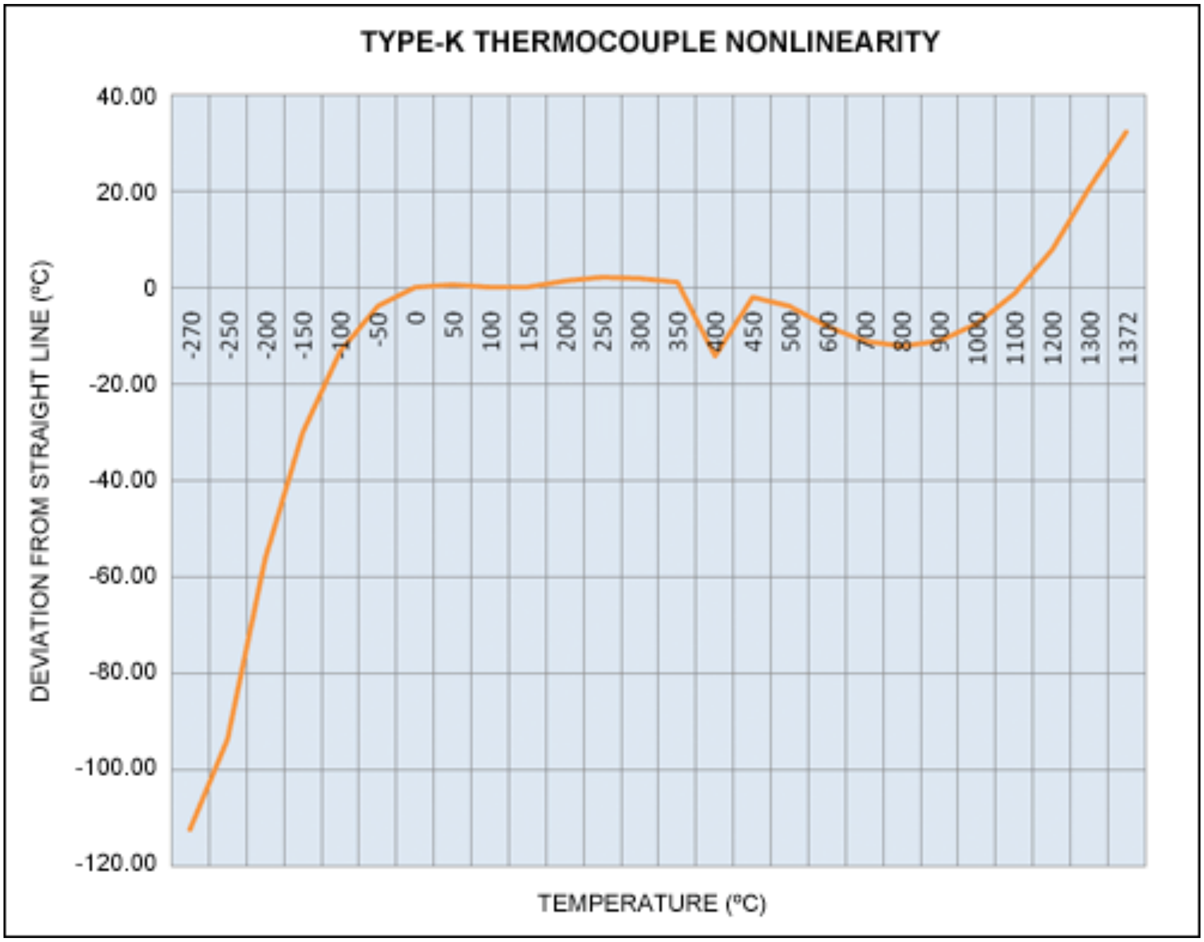


Figure 3 - K type thermocouple deviation from straight line approximation vs temperature

2.1.1 Mounting

The sensors will be mounted 1.5 inches below the cylinder port. Installation consists of first drilling and tapping a 1/8 inch hole in the exhaust manifold. A 1/8 inch NPT steel bung is centered on the tapped hole and welded to the exhaust manifold. This bung is threaded on the inside and once welded to the manifold, the EGT sensor can be screwed into the bung. The tip of the sensor fits through the 1/8 inch hole and into the exhaust manifold. The sensors should be placed as far away from any sources of electromagnetic interference (EMI) such as spark plugs, wires, and coils as possible. EMI noise may be induced into the probe wires. The figure below shows the tip of a thermocouple, and the threading that would be screwed into the bung.

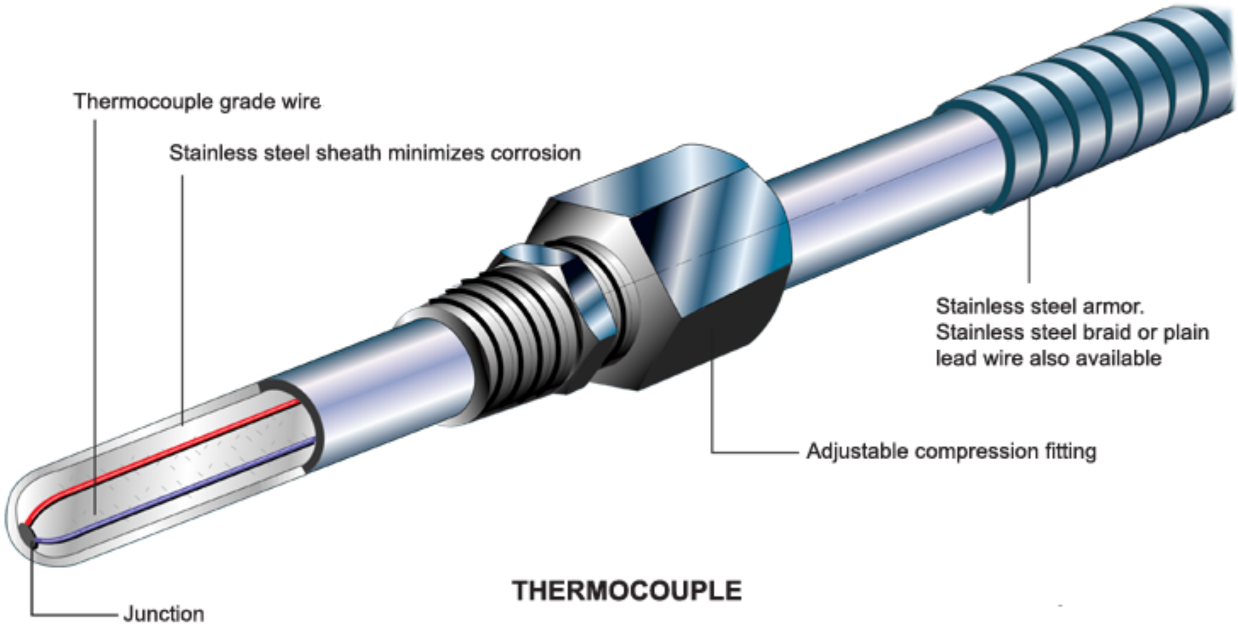


Figure 4 - Thermocouple sensor tip

2.2 Amplifier

Due to the thermocouples outputting their own voltage signal in the order of microvolts, we need to either use an extremely sensitive voltmeter or amplify the signal. In order to get a useful voltage reading from the thermocouples that are accurate for a 0-5V input, which is the voltage reading we need for the onboard Mega Squirt 3 computer, we need to amplify the signal. There were a few different options we explored en route to finding the optimal amplifier. These options consisted of designing our own amplifier, or using one of two prefabricated amplifiers; the EGT Quad Channel Amplifier (specially designed for this application) or the AD595 Amplifier. We had to carefully analyze which would be the most suitable option taking into consideration the following characteristics:

- Amplifying to the 0-5V voltage we need and the errors associated with each one
- Temperatures that the amplifiers can withstand if mounted on the FSAE car
- Cost
- Time constraints

2.2.1 EGT Quad Channel Amplifier

The EGT Quad Channel Amplifier amplifies the signal from an ungrounded Type K thermocouple up to a 0-5V signal. The onboard MS3 computer can read this voltage signal. Each thermocouple after amplification outputs a 4mV signal for every degree Celsius of change. If powered by 14.5-32V the Quad Amplifier can achieve the full temperature reading range of the Type K thermocouples (0°C to 1250°C). A graph of maximum temperature range versus power voltage is seen in figure 2.2.1.

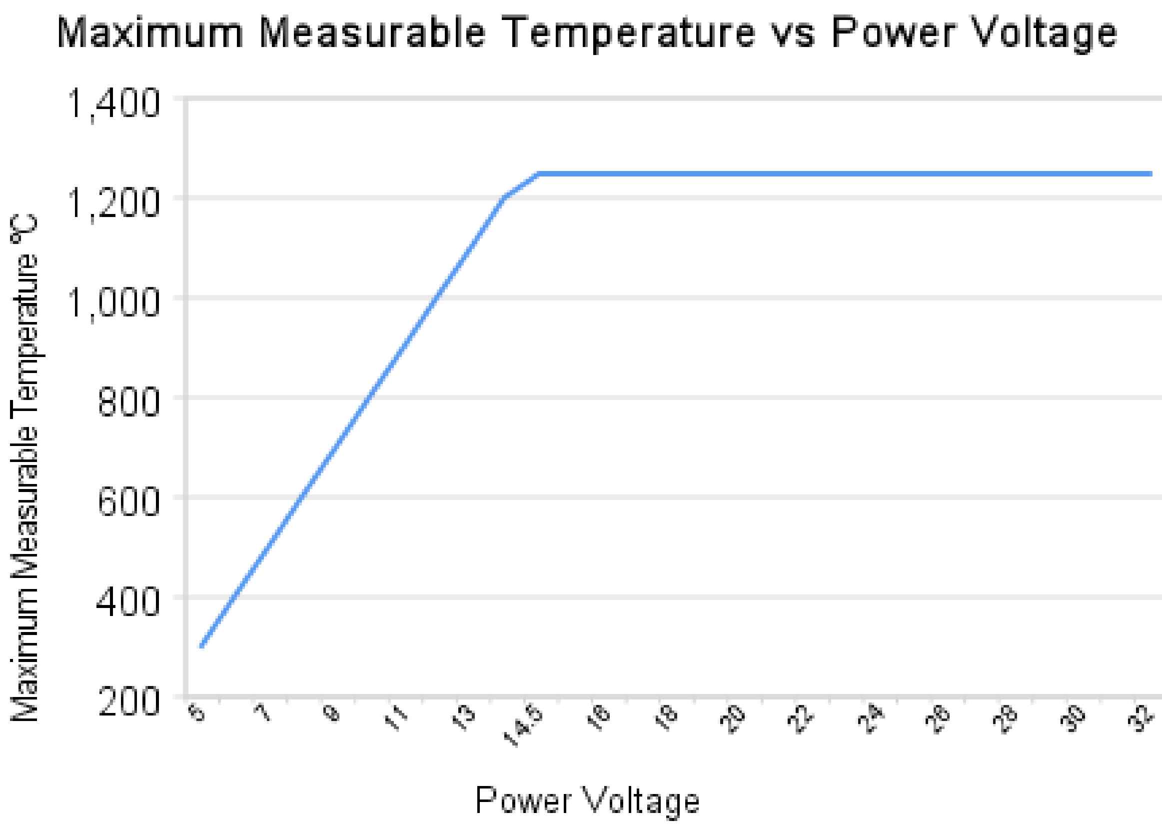


Figure 5: Max Measurable Temperature vs. Power voltage

The EGT Quad Channel Amplifier is restricted to an external ambient exposure temperature of 80°C. If the chip is exposed to higher than 80°C, the plastic enclosure may suffer serious damages. Due to the enclosure needing to be mounted on the FSAE car, it will most likely incur temperatures upwards of 50°C but we feel that we will be able to find a mounting placement where it will not be exposed to greater than 80°C. If that is not the case, providing heat shielding might be necessary. A perk of using the EGT Quad Channel Amplifier is that due to it being an analog signal it samples at an infinite frequency. Thus, the amplifier has a higher slew rate than the Type K thermocouple so the thermocouple sensor and not the amplifier limit response time.

If the amplifier gain error and offset error are calculated beforehand by zeroing the reading (putting the thermocouples in ice water at 0°C – voltage should read 0V). Any offsets and errors can be recorded and used in the temperature calculation in order to get precise readings.

When calibrating the temperature for this amplifier, we use the following equation:

Temperature °C = (Voltage / (0.004 * (1 + amplifier gain error))) - offset error
(Where the 0.004 in the function is the nominal 4mV / °C)

Lastly, the EGT Quad Thermocouple Amplifier requires no designing time with it being prefabricated, and costs $399.99. This package includes 4 Type K thermocouples.

2.2.2 AD595 Amplifying Chip

The AD595 Amplifying Chip was another possible candidate we explored for amplifying the 4 voltages being outputting from the thermocouples. When reading into this type of chip and comparing it to the EGT Quad Channel Amplifier, there were a few discrepancies that put us in favour of using the EGT Quad Channel Amplifier.

Firstly, the cold junction errors of the AD595 are relatively high. Voltage outputs coming from the amplifier were very dependent on the chip being in thermal equilibrium. If the chip was exposed to greater than 50°C there was a high possibility of damages and cold junction error. This compared to the EGT Quad Channel Amplifier was 30°C lower. This along with the fact that the AD595 does not come in a Quad Channel package with 4 Type K thermocouples included is enough reason to choose the EGT Quad Channel Amplifier.

The cost of purchasing this chip is around $40. However on top of buying the chip the K Type thermocouple wire has to be ordered. This costs $120 per 30 m.

2.2.3 Designing Our Own Amplifier

In order to design our own amplifier we would have to meet with specialty IC chip manufacturers and spend time coming up with a prototype and then optimizing it until we had a final product made. This could take months or even years. Unfortunately due to time constraints, this is not the best option for this project.

After exploring three possible solutions for amplifying our voltage signal from the thermocouples, we came to the conclusion that the most feasible solution is the EGT Quad Channel Amplifier.

2.3 Data Recording

In order to interpret the EGT data incoming from each temperature sensor, a microcontroller will need to be incorporated into the system. The microcontroller needs to be able to take in at least 4 analog inputs, one for each sensor, as well as be able to output the data to a display to give the user visibility to the sensor readings. Currently there are two options available for consideration:

1. Using the car's existing ECU, Mega-Squirt 3 Engine Management System.

2. Using an external Arduino microcontroller.

2.3.1 Design Justification

We decided to use the car's existing ECU, Mega-Squirt 3 in order to collect the data for the EGTs. The MS3 has a total of 5 available analog inputs. The FSAE team currently uses the MS3 interface to data log Coolant Temperature, Manifold Air Temperature, Air to Fuel Ratio, and Throttle Position. This leaves only one remaining input. We could data log one cylinder at a time; however, we want all the cylinders to be operating within similar temperatures. The best way to ensure each cylinder is undergoing similar combustion is to test them at the same time. This means that we will unplug 3 of the other data logging sensors on the vehicle when testing for the 4 cylinders EGTs.

The MS3 has onboard data logging capabilities and saves the data to an SD card, which can then be read on a laptop using MS3 software. The MS3 is also able to communicate live data through a serial connection to a laptop. The main reason to use our current ECU to record EGTs is that the MS3 software that we use has an interface built in for EGTs. A sample result from an 8-cylinder engine is shown below in Fig 1. This figure demonstrates how the EGTs can be displayed simultaneously with Throttle Position and Revolutions per Minute using the MS3 interface.

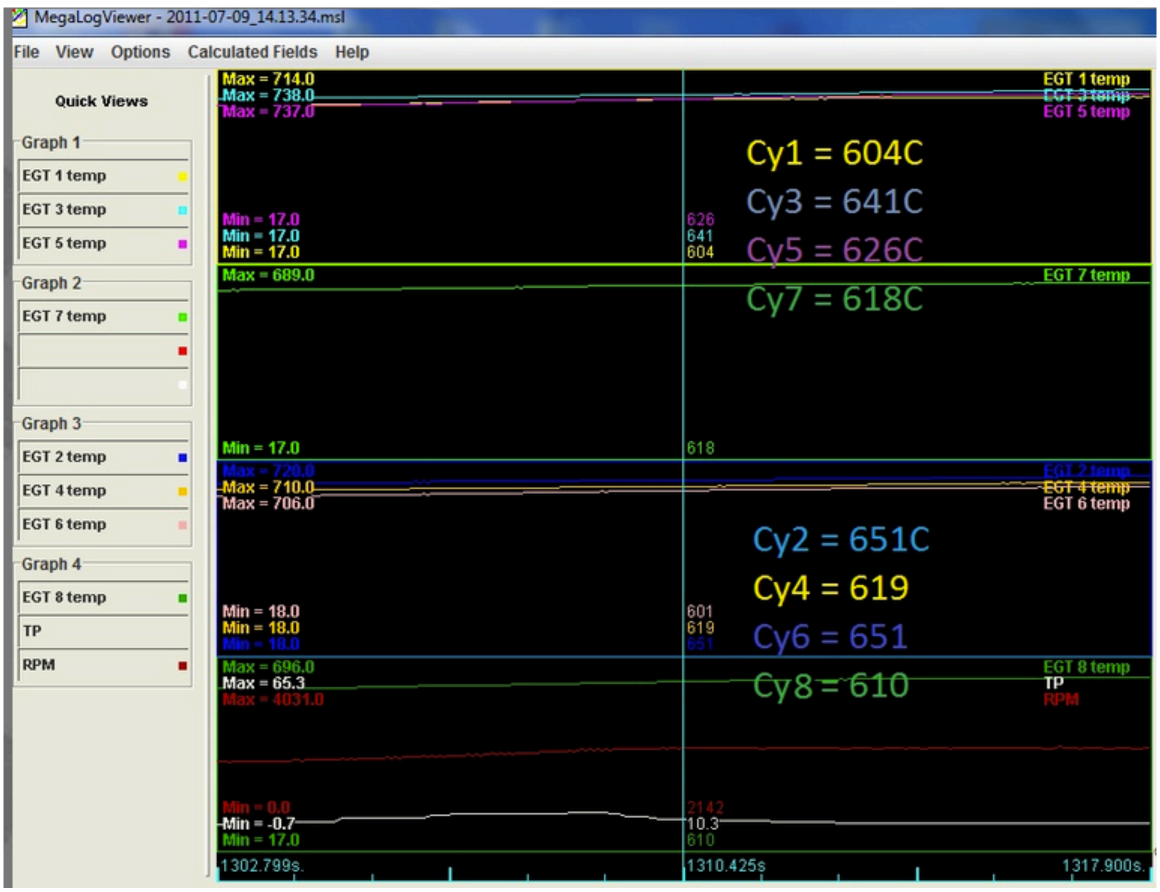


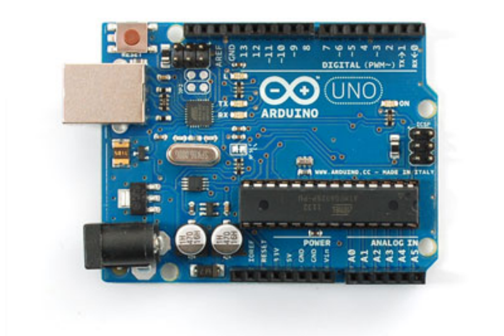
Fig 6 - Example of EGT reading using MS3 for 8-cylinder engine

2.3.2 Future Considerations for an External Data Logger

Ideally we would want to log the data for the EGTs as well as the other four inputs mentioned above. This is the main motivation for using an external Data Logger. However, our external Data Logger is a work in progress for the FSAE Electrical team. The FSAE Electrical Team is currently developing a Data Logger using an Arduino Uno R3. This external Data Logger will be valuable to the team for more than just EGTs.

The FSAE team is aiming to test both the EGTs and the Arduino Data-Logger simultaneously next semester. Currently the Arduino creates a mls The two projects are an adequate fit because our current MS3 ECU contains the ability to interpret Thermocouple Analog signals and display the results. In the future we will be able to import the data from the ECU into excel and compare it to the excel file supplied by the Arduino. We can use this comparison to see whether or not our Arduino Data-Logger is working or accurate.

2.3.3 Arduino Uno R3:



The Arduino Uno is a microcontroller board. It has 14 digital input/output pins and 6 analog inputs. It can be connected to a computer using a USB cable or can be powered by DC.

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328)
EEPROM	1 KB (ATmega328)
Clock Speed	16 MHz

Table 1 – Arduino Uno Microcontroller Specifications

Cost: $29.95

The FSAE team already has an Arduino Uno R3. However, should we wish to simultaneously data log more than 6 analog signals at once the FSAE team could run two separate data loggers.

3 Conclusions

3.1 Concluding Remarks and Future Work

The design discussed in this report will provide a solution to the EGT monitoring system. It is anticipated that this design be implemented in the future to provide the UVic Formula SAE team with better insight to their engines performance resulting in improved engine tuning. During the design process, factors like cost, equipment availability, existing data logging systems, and performance were all taken into consideration. Due to the limited budget of the Formula SAE team, cost of equipment affected our decisions drastically. It is recommended that the EGT Quad Channel package be purchased for the price of $399.99. It may not be the most inexpensive solution but the convenience of having a package kit justifies this purchase. It is our hope that the Formula SAE team will approve this design and the system will be built, tested and operational by February 2013. It is anticipated that the EGT monitoring system will ultimately result in improved engine performance and better results for the FSAE team at competition, however it is not yet known whether or not the EGT system will provide any useful data, or if the engine performance can be improved with this data.

3.2 Project Milestones

Table 1: Summary of accomplishments and dates

Accomplishments	Completion Date
First Group Meeting	2012-11-28
Dr. Tiedje agrees to be supervisor	12-10-10
Second group meeting	12-10-12
Interim report submitted	12-10-16

Meeting with Dr. Tiedje	12-11-16
Third group meeting	12-11-26
Website design	12-12-03
Final report submitted	12-12-03