Exhaust Gas Temperature Monitor For An Internal Combustion Engine

INTERIM REPORT

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1 Introduction

1.1 Exhaust Gas Temperature

Our ELEC 399 project will be to design and build an Exhaust Gas Temperature data collection system for the UVic Formula Motorsport racecar. The ability to measure the EGT's of each cylinder and then output those analog temperature signals to a graphical interface will help the UVic Formula Motorsport tune the engine. Monitoring EGTs against RPMs (Revolutions per Minute) will give a good indication of how lean or rich the engine is running. (Lean when the air to fuel ratio contains a lot of air. Rich when the air to fuel ration contains a lot of fuel.)

This report will introduce the FSAE competition and give a brief description of the University of Victoria's team. Then it will give a brief overview of engine tuning using UVic's tuning software. The report will then move on to describe EGTs, possible sensors, various data collection methods and then detail our projects milestones and timeline.

1.2 Formula SAE

The Society of Automotive engineers has more than 132,000 members – engineers, business executives, educators, and students – from more than 97 countries. Recognizing the need for engineering students to gain practical experience, the society has been hosting an annual design competition known as Formula SAE since 1981. The competition calls upon teams of university students to conceive, design, and fabricate a small formula-style race car, and compete against other universities in a number of static and dynamic events.

Design is governed by tactful restrictions, with the intent of stimulating the students' ingenuity and imagination. Each car is designed, built, and tested over the period of one year. Throughout the process, students develop their skills in design, analysis, fabrication, project management, budgeting, and leadership.

1.3 UVic Formula Motorsport team

The UVic Formula SAE team was formed in 2001, competing for the first time in 2002. Our team has successfully competed in one international Formula SAE collegiate competition every year since then. Each year our design and fabrication processes capitalize on the lessons learned from the previous year. This has resulted in significantly improved results. We produced the second fastest Canadian time in the Autocross event at 2012 FSAE Michigan. Every year the team strives to improve the car and their performances in each competition event while developing the necessary skills to run a race team.

This year the team plans to attend Formula SAE Lincoln from June 19th-22nd at the Lincoln Airpark in Lincoln, Nebraska. For this, the team is designing and building a new car, which we have named UV13. With the accumulation of knowledge and experience through the years, the team is in a position to strive for excellence.

UV13-Design Targets:

- *Target weight of 500lbs (previous iteration was 527 lbs)*
- *Superior cockpit ergonomics for a variety of driver sizes*
- *Ability to swap out engine / rear end in less than 1 hour*
- *Production quality, fit, and finish*
- *Enhanced use of data acquisition and analysis system*

1.4 UVic Engine Tuning

UVic Formula Motorsports uses a Naturally Aspirated Honda CBR 600 F4i fuelled by 94 Octane pump gas. Our team has plans to switch over to Formula Electric, however, UV13 will continue using the Honda CBR. As mentioned above, the specifications of the car, including the engine, are regulated by strict set of rules. A significant rule requires a restrictor be placed to limit the power capabilities from the engine. The restrictor cannot exceed 20.0mm and it must be placed in between the throttle and the engine so that all of the air must pass through it.

The restrictor is significant because it drastically affects the Air to Fuel ratio (AFR) thus affecting the internal combustion within the cylinders (ie: power). While this restrictor limits the amount of horsepower the engine is able to produce, we are able to tune the engine to compensate.

When tuning the engine we monitor the engine using a Dynamometer (dyno). The combination of the dyno and UV13's Engine Control Unit (ECU) allows us to monitor several engine characteristics simultaneously. The ECU used is called Megasquirt3 and will be briefly described later on. 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 we can 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)

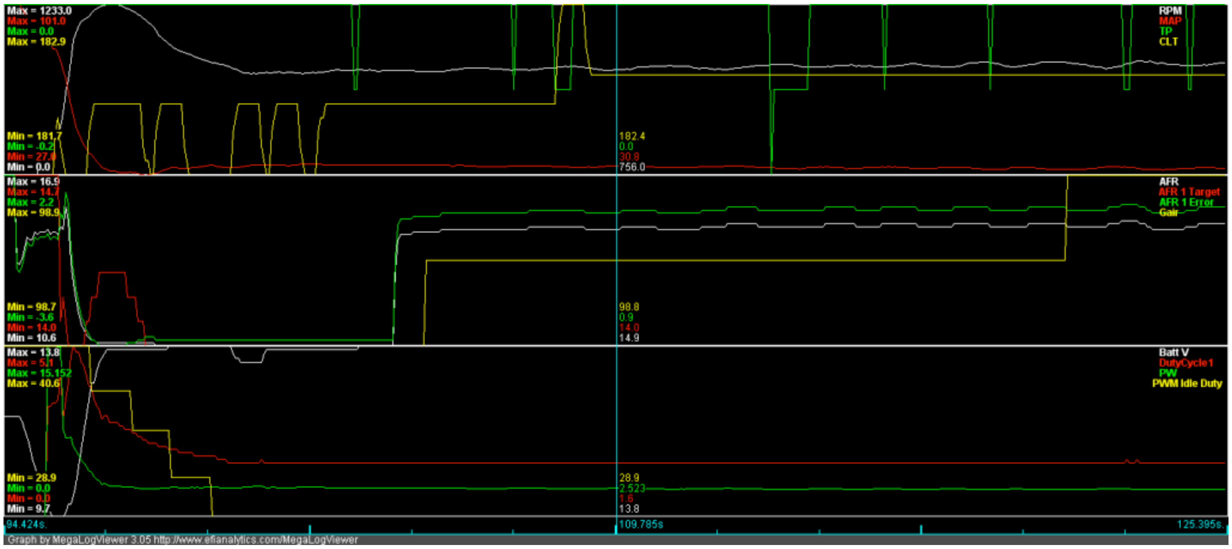


Figure 1 –Sample Output to Megasquirt3 software interface

There are basically three variables within our control using MS3 software when tuning an engine.

- 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.)

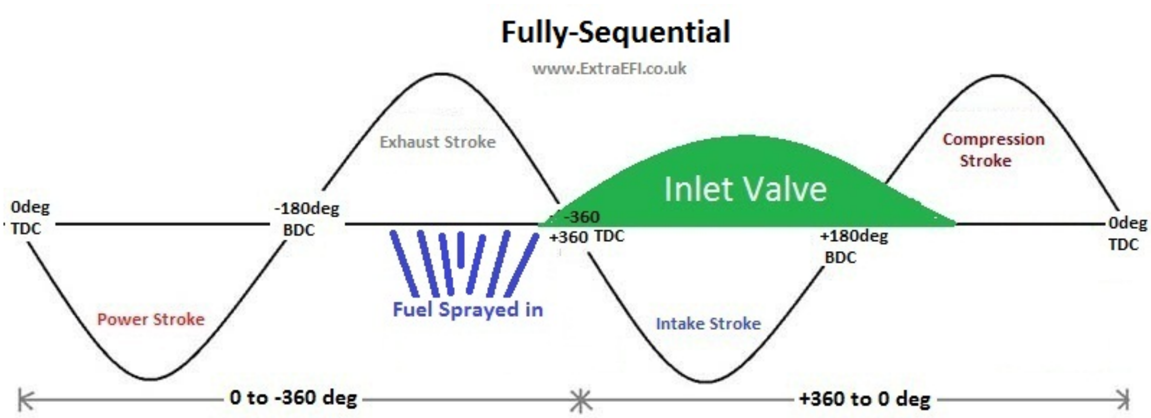
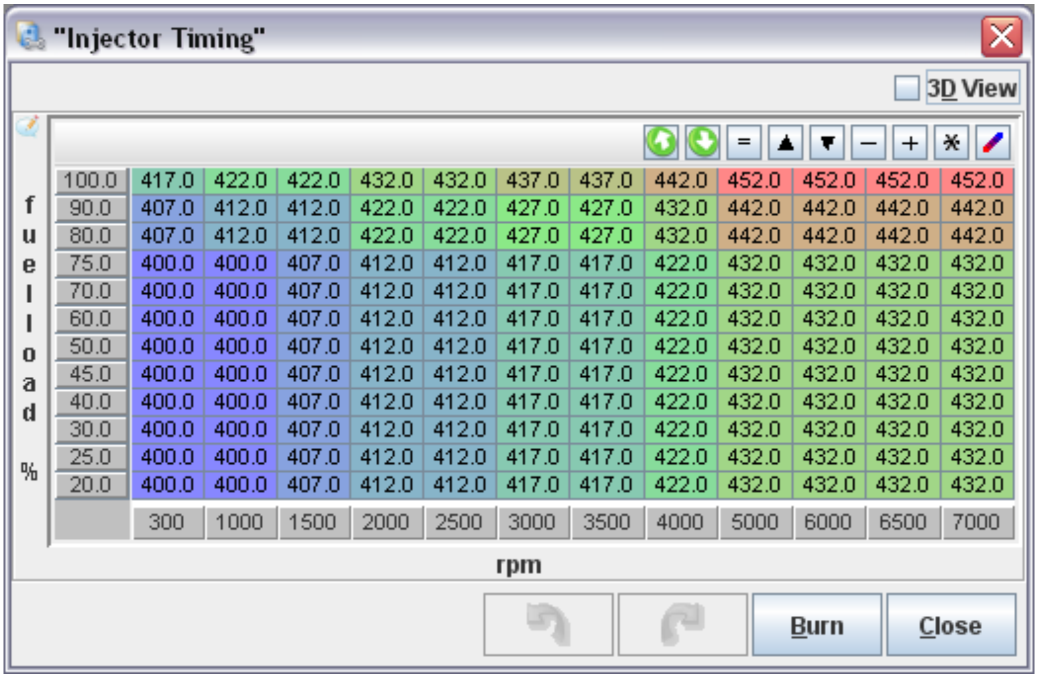


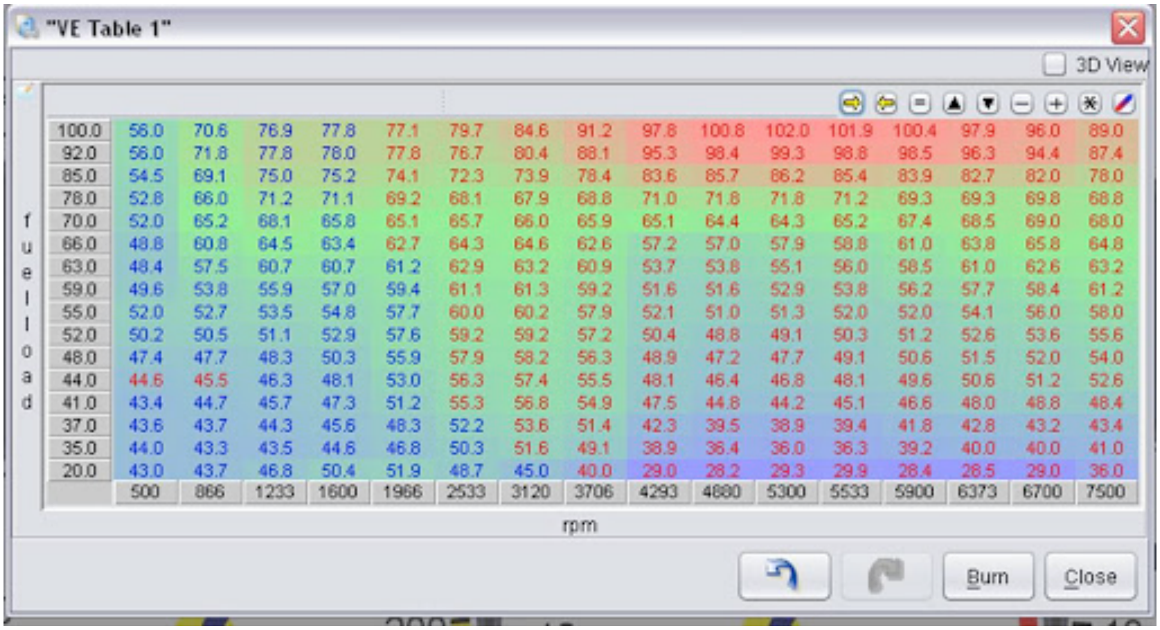
Figure 2 – Fully Sequential 720 deg timing for Otto Cycle



fuel load %	300	1000	1500	2000	2500	3000	3500	4000	5000	6000	6500	7000
100.0	417.0	422.0	422.0	432.0	432.0	437.0	437.0	442.0	452.0	452.0	452.0	452.0
90.0	407.0	412.0	412.0	422.0	422.0	427.0	427.0	432.0	442.0	442.0	442.0	442.0
80.0	407.0	412.0	412.0	422.0	422.0	427.0	427.0	432.0	442.0	442.0	442.0	442.0
75.0	400.0	400.0	407.0	412.0	412.0	417.0	417.0	422.0	432.0	432.0	432.0	432.0
70.0	400.0	400.0	407.0	412.0	412.0	417.0	417.0	422.0	432.0	432.0	432.0	432.0
60.0	400.0	400.0	407.0	412.0	412.0	417.0	417.0	422.0	432.0	432.0	432.0	432.0
50.0	400.0	400.0	407.0	412.0	412.0	417.0	417.0	422.0	432.0	432.0	432.0	432.0
45.0	400.0	400.0	407.0	412.0	412.0	417.0	417.0	422.0	432.0	432.0	432.0	432.0
40.0	400.0	400.0	407.0	412.0	412.0	417.0	417.0	422.0	432.0	432.0	432.0	432.0
30.0	400.0	400.0	407.0	412.0	412.0	417.0	417.0	422.0	432.0	432.0	432.0	432.0
25.0	400.0	400.0	407.0	412.0	412.0	417.0	417.0	422.0	432.0	432.0	432.0	432.0
20.0	400.0	400.0	407.0	412.0	412.0	417.0	417.0	422.0	432.0	432.0	432.0	432.0

Figure 3 – Injector Timing from MS3 interface

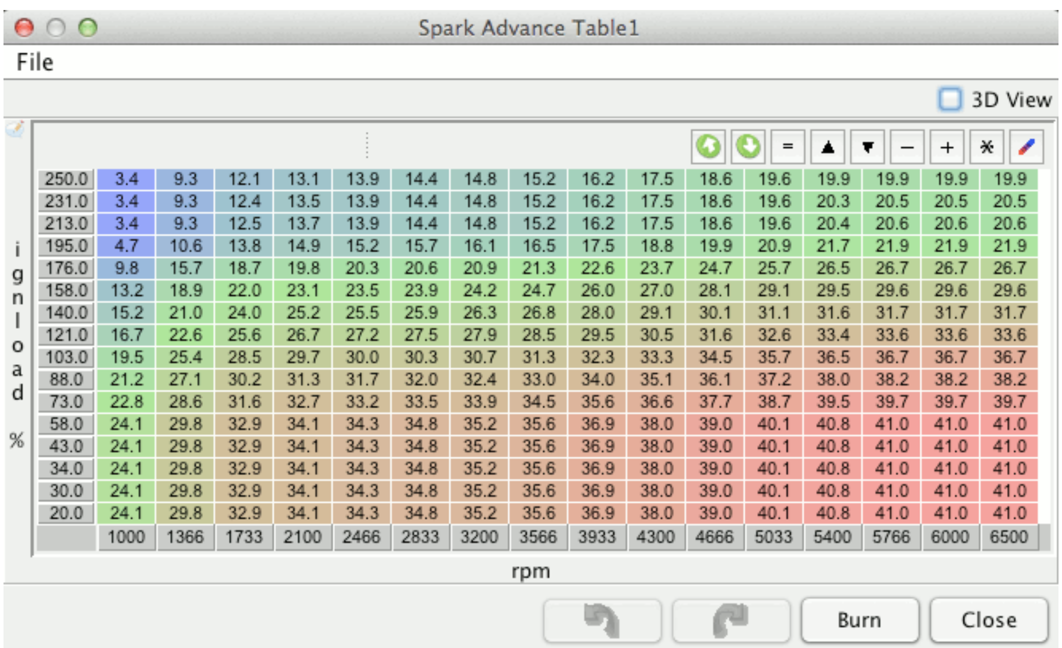
The Otto Cycle of each cylinder happens throughout 720 degrees of Cam Shaft rotation see Fig 2. This rotation is monitored using a CamSensor and is communicated to the ECU. Fig 3 shows the human interface device where the injector timing can be varied. Generally all of the fuel should be injected into the intake manifold 10 degrees prior to the valves opening. This varies with different RPMs and with different fuel loads.



fuel load \ rpm	500	866	1233	1600	1966	2533	3120	3706	4293	4880	5300	5533	5900	6373	6700	7500
100.0	56.0	70.6	76.9	77.8	77.1	79.7	84.6	91.2	97.8	100.8	102.0	101.9	100.4	97.9	96.0	89.0
92.0	56.0	71.8	77.8	78.0	77.8	76.7	80.4	88.1	95.3	98.4	99.3	98.8	98.5	96.3	94.4	87.4
85.0	54.5	69.1	75.0	75.2	74.1	72.3	73.9	78.4	83.6	85.7	86.2	85.4	83.9	82.7	82.0	78.0
78.0	52.8	66.0	71.2	71.1	69.2	68.1	67.9	68.8	71.0	71.8	71.8	71.2	69.3	69.3	69.8	68.8
70.0	52.0	65.2	68.1	65.8	65.1	65.7	66.0	65.9	65.1	64.4	64.3	65.2	67.4	68.5	69.0	68.0
66.0	48.8	60.8	64.5	63.4	62.7	64.3	64.6	62.6	57.2	57.0	57.9	58.8	61.0	63.8	65.8	64.8
63.0	48.4	57.5	60.7	60.7	61.2	62.9	63.2	60.9	53.7	53.8	55.1	56.0	58.5	61.0	62.6	63.2
59.0	49.6	53.8	55.9	57.0	59.4	61.1	61.3	59.2	51.6	51.6	52.9	53.8	56.2	57.7	58.4	61.2
55.0	52.0	52.7	53.5	54.8	57.7	60.0	60.2	57.9	52.1	51.0	51.3	52.0	52.0	54.1	56.0	58.0
52.0	50.2	50.5	51.1	52.9	57.6	59.2	59.2	57.2	50.4	48.8	49.1	50.3	51.2	52.6	53.6	55.6
48.0	47.4	47.7	48.3	50.3	55.9	57.9	58.2	56.3	48.9	47.2	47.7	49.1	50.6	51.5	52.0	54.0
44.0	44.6	45.5	46.3	48.1	53.0	56.3	57.4	55.5	48.1	46.4	46.8	48.1	49.6	50.6	51.2	52.6
41.0	43.4	44.7	45.7	47.3	51.2	55.3	56.8	54.9	47.5	44.8	44.2	45.1	46.6	48.0	48.8	48.4
37.0	43.6	43.7	44.3	45.6	48.3	52.2	53.6	51.4	42.3	39.5	38.9	39.4	41.8	42.8	43.2	43.4
35.0	44.0	43.3	43.5	44.6	46.8	50.3	51.6	49.1	38.9	36.4	36.0	36.3	39.2	40.0	40.0	41.0
20.0	43.0	43.7	46.8	50.4	51.9	48.7	45.0	40.0	29.0	28.2	29.3	29.9	28.4	28.5	29.0	36.0

Figure 4 - Volumetric Efficiency Table from MS3 interface

This human interface device allows you to manipulate the ECU's targeted air to fuel ratio for various rpms. See Fig 4.



ign load % \ rpm	1000	1366	1733	2100	2466	2833	3200	3566	3933	4300	4666	5033	5400	5766	6000	6500
250.0	3.4	9.3	12.1	13.1	13.9	14.4	14.8	15.2	16.2	17.5	18.6	19.6	19.9	19.9	19.9	19.9
231.0	3.4	9.3	12.4	13.5	13.9	14.4	14.8	15.2	16.2	17.5	18.6	19.6	20.3	20.5	20.5	20.5
213.0	3.4	9.3	12.5	13.7	13.9	14.4	14.8	15.2	16.2	17.5	18.6	19.6	20.4	20.6	20.6	20.6
195.0	4.7	10.6	13.8	14.9	15.2	15.7	16.1	16.5	17.5	18.8	19.9	20.9	21.7	21.9	21.9	21.9
176.0	9.8	15.7	18.7	19.8	20.3	20.6	20.9	21.3	22.6	23.7	24.7	25.7	26.5	26.7	26.7	26.7
158.0	13.2	18.9	22.0	23.1	23.5	23.9	24.2	24.7	26.0	27.0	28.1	29.1	29.5	29.6	29.6	29.6
140.0	15.2	21.0	24.0	25.2	25.5	25.9	26.3	26.8	28.0	29.1	30.1	31.1	31.6	31.7	31.7	31.7
121.0	16.7	22.6	25.6	26.7	27.2	27.5	27.9	28.5	29.5	30.5	31.6	32.6	33.4	33.6	33.6	33.6
103.0	19.5	25.4	28.5	29.7	30.0	30.3	30.7	31.3	32.3	33.3	34.5	35.7	36.5	36.7	36.7	36.7
88.0	21.2	27.1	30.2	31.3	31.7	32.0	32.4	33.0	34.0	35.1	36.1	37.2	38.0	38.2	38.2	38.2
73.0	22.8	28.6	31.6	32.7	33.2	33.5	33.9	34.5	35.6	36.6	37.7	38.7	39.5	39.7	39.7	39.7
58.0	24.1	29.8	32.9	34.1	34.3	34.8	35.2	35.6	36.9	38.0	39.0	40.1	40.8	41.0	41.0	41.0
43.0	24.1	29.8	32.9	34.1	34.3	34.8	35.2	35.6	36.9	38.0	39.0	40.1	40.8	41.0	41.0	41.0
34.0	24.1	29.8	32.9	34.1	34.3	34.8	35.2	35.6	36.9	38.0	39.0	40.1	40.8	41.0	41.0	41.0
30.0	24.1	29.8	32.9	34.1	34.3	34.8	35.2	35.6	36.9	38.0	39.0	40.1	40.8	41.0	41.0	41.0
20.0	24.1	29.8	32.9	34.1	34.3	34.8	35.2	35.6	36.9	38.0	39.0	40.1	40.8	41.0	41.0	41.0

Figure 5 - Spark Advance Table from MS3 interface

This interface allows you to control how early the spark ignites before the cylinder reaches top dead center. Adjusting this without understanding engine timing can damage an engine. See Fig 5.

1.5 Motivation for Monitoring EGT

Generally speaking if the Exhaust Gas Temperatures are high this indicates that the Air to Fuel Ratio (AFR) are lean and that there is too much air in the mixture. If the temperatures are low it indicates the AFR is rich and that there is a surplus of fuel in the mixture.

The above is not always true. In some situations if the AFR is too lean the combustion temperature can go down. In some combustion situations if there is far too much oxygen in the reaction the temperatures can go down, even though it is leaner. For example in acetylene combustion reactions the oxygen can be increased enough so that the flame will go out.

It is also worth noting that an extremely efficient combustion reaction will produce some of the hottest flames. Generally when observing EGTs one should be aware of the extremes.

A clear benefit of knowing the EGT per cylinder is that you can see disparities between each cylinder. Ideally each cylinder will have a similar EGT. If the temperatures are not within 50°-100° C the cylinder can be tuned separately so that they are acting under the same conditions. Having similar EGTs within each cylinder will help smooth out the power distribution to the crankshaft. This can help the engine last longer and most likely output more power.

2 Design Concept

2.1 Exhaust Gas Temperature Sensor

We are currently researching different types of temperature sensing devices that we can use in the exhaust ports. There are several different temperature sensing devices that can be used for this application, each with their own pros and cons. The most commonly used devices include:

- Resistance Temperature Detectors (RTD),
- Thermistors, and
- Thermocouples.

The resistance temperature detection device is a very fine wire encased in a container, or bulb. When the temperature of the bulb changes, the electrical resistance in the wire changes proportionately. By passing a small current through this wire and measuring the resistance, the temperature can be determined. The advantage of using an RTD is they are a very accurate temperature sensing device however, at the same time they can be delicate if not handled carefully. According to different sources, using RTD's is not generally recommended for rough service (like on a kart). Moreover, due to the extremely high temperature of the exhaust gas temperature (EGT), an RTD that would be able to withstand this temperature could be costly.

Thermistors again are extremely accurate in determining temperature however they too are limited by exposure temperature. They are recommended for temperatures between 50-120 degrees Celsius.

The final device for temperature measurement is the thermocouple. There are several different types of thermocouples, using different materials for different temperature ranges, but they all operate by similar means. A thermocouple consists of two wires, of different materials fused together. For the high temperature range the thermocouples will be exposed to in the exhaust ports, the type K thermocouple appears to be the most suitable thermocouple with a maximum exposure temperature of 1900 degrees Fahrenheit. In a type K thermocouple one wire is an alloy called Chromel, and the other an alloy called Alumel. A small portion of each wire is exposed and the two are fused together. This section is encased in an electrically insulated sheath and the other ends of the wires are connected to a very sensitive voltmeter. When the fused end of the thermocouple wire is heated, it generates its own current. The voltage generated is an accurate indicator of the temperature of the end of the thermocouple once proper calibration is done. One of the biggest advantages of the thermocouple is its durability. With no delicate parts to break, unless you exceed their maximum temperature, they are extremely tough to damage. Thus, when determining which type of temperature sensing device we use, we will have to consider two main constraints. These constraints include making sure to not disrupt the flow of exhaust through the headers and ports upon installation and making sure the sensors will be able to withstand the exposure temperatures. These constraints will require further design research.

2.2 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.

Using the Mega-Squirt 3 Engine Management System (MS3) has considerable benefits. 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 FSAE team regularly uses this system during testing to get readings on things like fuel consumption and spark timing. It would be beneficial to the team if the EGT measurements were displayed concurrently with the other test measurements on the MS3 software. The

MS3 however, has only 1 available 0-5V analog input. This creates a potential problem, as our project requires 4 separate analog temperature readings from the exhaust header.

The second option requires using an external Arduino microcontroller to read the temperature sensors. Unlike the MS3, the Arduino has enough inputs to read all 4 analog temperature signals. The Arduino is able to display live data to a laptop using MATLAB. Downsides of using an external controller are the engine will have to be stationary during testing, and the data would be displayed in a separate location than the other measurements being tested.

3 Conclusions

3.1 Concluding Remarks

This report has outlined the basic design strategy of an exhaust gas temperature monitoring system. The motivation of this project is to improve engine efficiency and performance for the UVic formula SAE racecar. By implementing an EGT monitoring system, the FSAE team will have more visibility to the engine's behavior, allowing the team to better tune the engine for performance. By implementing the design strategy outlined in this report, we expect to have an operational EGT monitoring system at the end of the project. Our current design challenges are to determine the optimal thermal sensors to use for EGT measurements, and to design a microcontroller based system that can record the data from the sensors, and present it to the formula SAE team in an effective manner.

3.2 Project Milestones

A detailed project plan with dates is summarized in Table 1 and Figure 6.

Table 1: Summary of tasks and dates

Tasks	Planned Completion Date	Actual Completion Date
Complete background research	12-10-12	12-10-12
Report 1 – project introduction	12-10-16	12-10-16
Further studies on the project – price, tools, parts and designs	12-11-05	
Order parts	12-11-05	
Model making and testing	12-11-18	
Website design	12-12-02	
Final report	12-12-02	

Figure 6: Project milestones