Design of a portable steering wheel angle measurement system

Johan Svensson

Vehicle Dynamics
Aeronautical and Vehicle Engineering
Royal Institute of Technology

Master Thesis

TRITA-AVE 2015:07
ISSN 1651-7660
Abstract

The aim of this Master Thesis is to develop a steering wheel measuring system. The system should be easy to use and install, portable and have the possibility to be used in different vehicle types from different manufactures. The old system in use is stationary equipment that is difficult to apply on a new vehicle without any major installation.

In this work a prototype is developed using rate sensor technology. The system is based on two different angular rate sensors. One sensor is mounted on the steering wheel to record the motions the driver affects on the steering wheel. The second sensor is mounted fixed in the vehicle to record the movement of the vehicle. The signals are conditioned and combined before conversion into the steering wheel angle. The system is compatible with Race Technology DL2 data logger.

The work presented shows that the design of the prototype works satisfactory, although with some limitations. Further development has to be done to make the system able to measure higher steering wheel angular velocities. Additional sensors can also be embedded in the system to minimize the signal conditioning after the measurements.
Acknowledgment
This master thesis was carried out at the vehicle-engineering department at the Royal Institute of Technology (KTH). Most of the work was carried out during 2008.

I want to thank the department for their patience during the tumbling years of 2008 and 2009. Especially to my supervisor Andreas Nilsson.

I want to thank the helpful people at company referred to as A, B, C, D and E.

A good luck and thank you to my former boss, Daniel Håkansson at EFFYH Engine Development AB who took me on an interesting but short journey.

And most important. My wife Sandra, I love you. Thank you for caring. Thank you for the life of my daughter Sia.
Contents

1 Background ............................................................................................................................. 1
  1.1 Objective ........................................................................................................................... 1
2 Review of available systems ................................................................................................... 3
  2.1 Systems in use today ........................................................................................................ 3
  2.2 Technology of available systems ..................................................................................... 6
  2.3 Measurement technologies and setups ............................................................................. 8
3 Specification of selected system ........................................................................................... 13
  3.1 System design ................................................................................................................. 13
4 Installation and use ................................................................................................................ 17
  4.1 Installation procedure ..................................................................................................... 17
  4.2 Measurement procedure ................................................................................................. 18
  4.3 Retrieving Data .............................................................................................................. 18
  4.4 Adjusting results ............................................................................................................. 24
5 Results ................................................................................................................................... 25
  5.1 Raw data ......................................................................................................................... 25
  5.2 Correlated data ............................................................................................................... 26
  5.3 Comparison of rate signals ............................................................................................. 27
  5.4 Double lane change ........................................................................................................ 27
  5.5 Measurement errors ........................................................................................................ 29
6 Discussion and conclusions ................................................................................................... 31
7 Recommendations for future work ........................................................................................ 33
  7.1 Measurement range ........................................................................................................ 33
  7.2 Angle of zero .................................................................................................................. 33
  7.3 Wireless .......................................................................................................................... 33
8 References ................................................................................................................................ 35
1 Background

The vehicle department at KTH (the Royal Institute of Technology) is interested to get a new system to measure the steering angle in a vehicle. A portable system suitable for different cars is preferred over a stationary installation. The main use of the steering angle measurement system is educational. Every year test track data are collected as a part of the education. The data acquisition system that is currently in use in the present test vehicle is outdated and requires lot of work to fit to a new vehicle. Therefore a completely new mobile data acquisition system has been purchased. The new system is a Race Technology DL2 with integrated sensors, including a GPS. This system has all the sensors required for measuring vehicle characteristics, except for measuring the angle of the steering wheel.

The steering input subsystem is decided to either be purchased from an existing manufacturer of vehicle measurements systems or be developed at the vehicle department. The demands on the system are set high regarding mobility, adaptability, easy to use and with a minimum impact on the driver.

1.1 Objective

The market of vehicle measuring systems is quite limited and is dominated by a couple of manufacturers mostly from Europe and North America. Their main market targets are vehicle manufacturers and vehicle subsystem development. This means that the driver in most cases are used to the different systems. It is preferred that the new system does not affect the driver in any unwanted terms such as danger to the driver or dangerous driving behaviour, since an inexperienced driver such a student or a recruited test person are the main users. The decision of buying a complete factory system or construct one from scratch is based on the fulfilment of the system requirement and the availability of different systems.

The main system requirements for the system are set through discussions between the faculty of the vehicle department and the author.

1.1.2 System requirements

- Be compatible with the most cars on the market, especially SAAB and Volvo
- Easy to install and detach.
- Easy to calibrate.
- Easy to use.
- Be compatible with a data acquisition unit.
- Measure at least full angle of one full revolution (± 180°).
- Neither distracts nor affects the driver during driving.
- Use the original steering wheel of the test vehicle.
- Measurement accuracy ±1°.
- Achieve to measure during high angular acceleration.
- Capable of angular velocities up to at least 500º/s
1.1.3 Optional requirements

- Measure the steering wheel angle lock to lock.
- Not affect the steering feel much regarding moment of inertia, friction etc.
- Not obstruct the passenger compartment.
- Capable of angular velocities up to 1000°/s

The system requirements were set prior to any major research of available of-the-shelf products.
2 Review of available systems

2.1 Systems in use today
A thorough investigation is made to get an overview of the products and solutions that is in use at vehicle companies. Different companies within the sector are contacted and a few of them can provide information regarding their measuring systems. They are referred to as followed due to some sensible information that was received:

Company A, Swedish brand
Company B, Swedish brand
Company C, German brand
Company D, German brand
Company E, Swedish brand

2.1.1 Company A
Company A has many different systems in use for measuring of steering wheel angles in. The company could provide very little information on what system they were using. A master thesis regarding a combined angular and torque snap-on steering wheel have been performed. Company A also has a steering robot from the company Vehi.Co. in use, see Figure 1[1]. The steering robot can be used to record the input from the driver as well as handling the vehicle after a predefined driver program.

Figure 1: Vehi.Co steering robot [1].
2.1.2 Company B

Company B has through the years been using a variety of configuration and setups to measure the steering angle. The information from this company is complete and involves both products that have been in use and are in use. It is also known that Company B use the same procedures and technologies as their American owner. The equipment that is mostly in use by this company is the RMS steering wheel and the snap on steering wheel from Sensor Development Inc. as seen in Figure 2 [2].

![Figure 2: Sensor Development snap on steering wheel [2].](image)

2.1.3 Company C

The German Company C have two systems in use. An identical to the one used by Company B from Sensor Development Inc. and a similar system from the company Corrsys-Datron called MSW as seen in Figure 3 [3].

![Figure 3: Corrsys Datron snap on steering wheel MSW [3].](image)
2.1.4 Company D
Company D has three systems in use. The main difference from the other companies presented here is that Company D use only one system bought off-the-shelf, a replacement steering wheel from the company Caesar Datensysteme. Two other systems has been developed in-house and one more system is currently under development. The new system has the highest specified accuracy of the systems reviewed here and is presented in Figure 4.

![Figure 4: The future steering wheel from Company D](image)

2.1.5 Company E
The Company E test facilities generally use steering robots. For cases when they are not, they have in-house developed replacement steering wheels. These are quite simple and are using potentiometric technology. However, it is very hard to make these compatible with general passenger cars as they are built out of truck parts.
2.2 Technology of available systems

The following tables are an assembly of the products that are in use at different companies. Table 2 is the continuation of Table 1.

Table 1: The measurement systems

<table>
<thead>
<tr>
<th>Developer</th>
<th>Type</th>
<th>Technology</th>
<th>Resolution</th>
<th>%/s</th>
<th>Signal</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Försvarets Flygtekniska Anstalt</td>
<td>Replacement wheel, no AirBag</td>
<td>Unknown</td>
<td>0,25°</td>
<td>unknown</td>
<td>± 10V</td>
<td>unknown</td>
</tr>
<tr>
<td>Reglerungs und Messtechnik</td>
<td>Replacement wheel, no AirBag</td>
<td>Capsuled optical</td>
<td>0,50%</td>
<td>± 400</td>
<td>± 5V</td>
<td>€ 21290</td>
</tr>
<tr>
<td>Sensor Developments Inc.</td>
<td>SnapOn, AirBag compatible</td>
<td>Capsuled optical</td>
<td>0,05° - 0,2°</td>
<td>± 1000</td>
<td>± 5V</td>
<td>$ 17850</td>
</tr>
<tr>
<td>(classified)</td>
<td>SnapOn, AirBag compatible</td>
<td>Potentiometric</td>
<td>unknown</td>
<td>unknown</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>Vehi.Co</td>
<td>Steering robot/SnapOn</td>
<td>Capsuled optical</td>
<td>0,05°</td>
<td>± 1200</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>(classified)</td>
<td>SnapOn</td>
<td>Potentiometric</td>
<td>unknown</td>
<td>unknown</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>CorrSys-Datron</td>
<td>SnapOn/Replacement, AirBag</td>
<td>Capsuled optical</td>
<td>0,05°</td>
<td>± 1000</td>
<td>± 5V</td>
<td>unknown</td>
</tr>
<tr>
<td>(classified)</td>
<td>SnapOn, no AirBag</td>
<td>Magnetic sensor</td>
<td>0,1°</td>
<td>± 1000</td>
<td>unknown</td>
<td>€ 4000</td>
</tr>
<tr>
<td>(classified)</td>
<td>SnapOn, AirBag</td>
<td>Capsuled optical</td>
<td>0,02°</td>
<td>unknown</td>
<td>unknown</td>
<td>&lt;€ 5000</td>
</tr>
</tbody>
</table>

Table 2: Measurement comments

<table>
<thead>
<tr>
<th>System</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFA</td>
<td>Not in use, Limited steering column compatibility, Torque</td>
</tr>
<tr>
<td>RMS FEL 20</td>
<td>MOMO based, quite light weight, in use, Torque</td>
</tr>
<tr>
<td>No. 01184</td>
<td>Offsets the steering wheel, light weight, in use, Torque</td>
</tr>
<tr>
<td>(classified)</td>
<td>Offsets the steering wheel, light weight, in use, Torque</td>
</tr>
<tr>
<td>Lenkmachine</td>
<td>Steering robot</td>
</tr>
<tr>
<td>(classified)</td>
<td></td>
</tr>
<tr>
<td>MSW</td>
<td>Replace and offsets steering wheel, huge offset, Torque</td>
</tr>
<tr>
<td>Caesar CL</td>
<td>Audi steering wheel with adapters, Torque, x-y-z acceleration</td>
</tr>
<tr>
<td>(classified)</td>
<td>Insert in OE wheel, completely invisible for driver, no airbag</td>
</tr>
<tr>
<td>(classified)</td>
<td></td>
</tr>
<tr>
<td>(classified)</td>
<td>Low offset, OE feeling, under development</td>
</tr>
</tbody>
</table>

Replacement steering wheels or snap-on systems are the solutions that are most popular at the studied companies for studies of the input steering wheel angle. Most of the devices in use also measure the input torque from the driver. This is of interest when you want to know the driver effort when manoeuvring the vehicle. For the application of the system at KTH the torque is not the main objective, mobility and transparency is.
2.2.1 Effect on driver
All add-on systems that measure the steering angle have drawbacks that will affect the driver in some way or another. In the study of the available products it is also investigated in what way the systems affects the driver. A general answer from test personnel at different companies is that all snap-on steering wheels introduce an offset which can make it quite difficult to find a good driving position. A professional test driver can compensate for this as he or she is used to the system. If it is wanted to do a research and test that includes inexperienced drivers it can be problematic. It is hard to use subjective evaluation since the driving situation differs from a normal driving position. Snap-on steering wheels can also slide on the actual steering wheel and not only give faulty measurement results; it can also damage the steering wheel. Some snap-on steering wheels also makes it hard to reach different controls in the car such as turning indicators, lights and car horns. Figure 5 illustrate these problems very well.

![Figure 5: Very large offset at Corrsys-Datron MSW in a VW [3].](image)

The most driver transparent measurement systems among the one studied is the replacement steering wheel, especially those with a design very close to the original steering wheel such as the Caesar CL and the Company D steering wheels. These systems have hardly any negative effect on the driver as long it does not come to crashing as they have no air bags. The Company D wheel even has the stereo and hands free controls intact. Both these steering wheels can be in use if it is wanted to get a general opinion from an inexperienced crowd.

2.2.2 The KTH system
The requirement on the system that is going to be used at KTH is quite high set. It is surprisingly none of the systems that matches all the demands from KTH. The prices are considered to be too high. Therefore it is decided that a system will be developed and constructed at KTH.
2.3 Measurement technologies and setups

The different technologies demands different setups depending on the technology it is based on. The general potentiometric snap on setup has a belt, chain or wire going from the steering wheel to a potentiometer as seen in Figure 6. With this solution it can be a problem to attach the sensor in a good way. The most used way to attach the belt driven sensor is a suction cup on glass. Company A has a pole nearby going from floor to ceiling with the belt driven sensor attached to it. Thus, the front passenger compartment is not always accessible for passengers.

![Figure 6: Company B in house product showing wire system.](image)

A driver transparent way to measure an angle is to use some sort of hollow sensor around the steering column. However, a disadvantage is that it is necessary to make an installation which involves removing the steering wheel or some other procedures to reach the steering column. The measurement system has to be safe to the driver; most of the snap-on solutions do not allow the presence of an airbag. A replacement steering wheel is a solution if you want a genuine feeling of the vehicle as there are no strange offsets or measurement equipment that can distract the driver. However, the installation is demanding and an airbag was not included in the products either.

2.3.1 Compatibility for different cars

The installation requirement is one of the most significant demands. The interior design of a car and especially the driver compartment are different by brand, model and manufacturing year. There are more flat surfaces that you can mount your devices on in older cars. However, there is an area that is very similar between most cars when comparing different brands and models. It is the upper area of the steering wheel as marked in Figure 7.
The consequent area on the steering wheel has a big influence of which technology is used as it has limitations for some technologies.

2.3.2 IR sensor

An infra red (IR) transmitter/receiver can be mounted on either the dashboard or on the steering wheel. The device sends an infrared ray of light that can be reflected back to the receiver function. The IR device can be used with a circular disc with marks divided evenly at the edge. When turning the steering wheel you get an impulse that can be used as an angular velocity. By integrating the signal you get a steering angle. The advantage of this system is that the technology is quite simple. A range of companies sells the ingoing parts to these devices, although the circular disc has to be constructed and adjusted to fit the vehicle. The most convenient way would to mount the disc on the steering wheel and the receiver/transmitter on the dashboard. The drawbacks are that the inconsequence between different cars makes it quite hard to make a disc that fits all kind of steering wheels. The receiver/transmitter is also hard to mount on the same place on the dashboard in different cars. It is quite limited space behind the steering wheel, the coning of the steering wheel and the levers are a problem. It is very difficult to mount this device without removing the steering wheel. It also exists variants of IR sensors that read a predefined pattern on a circular disc in the same way as an EAN scanner. From this system you get the angle directly. A problem with these systems is that they often are capsulated and the receiver/transmitter must be very close to the disc as seen in Figure 8. This system works best in a belt or chain construction because of the capsulated setup.

Figure 8: Heidenhain sensor [6].
2.3.3 Hall sensors
A hall sensor is a magnetic system. It is similar to the IR system in the way that it can be used with a circular disc on the steering wheel and a magnetic hall sensor on the dash. Instead of a pattern on the disc the hall sensor senses differences on a magnetic materials thickness or a pattern of holes. The disc mounted on the steering wheel can have holes or teeth at the edge. The major problem with this system is that the sensor must be very close to the disc. The application suites best in a belt or chain application.

2.3.4 Optical reading
Optical sensors have different appearance depending on the usage. It exist some prototypes that use a camera and a pattern on the steering wheel, Figure 9. The big drawbacks are the fact that the driver can shadow the pattern when driving and the complicated technology that has to be used when analyzing the pattern from the recorded film. The capsulated optical sensors examined have the drawback of being a closed loop, such as a disc. It is a simple solution if mounted around an axle. The requirements here do not support that solution because of the difficulties by removing a steering wheel with an airbag. Optical sensors can have both embedded IR or light reflection sensors.

![Figure 9: Camera tracking [7].](image)
2.3.5 Potentiometric sensors

Potentiometric sensors can be used to measure angle on steering wheel in different ways. The technique is to vary the resistance of a supply voltage when actuated. The current test vehicle system uses a potentiometric device that is operated by a string around the steering wheel axle, see Figure 10. Some of the snap-on wheels have these features as well. The potentiometer is not interesting in this case due to the possible removal of the steering wheel.

![Figure 10: The potentiometric sensor that are in use today at KTH.](image)

2.3.6 Rate sensors

There are different types of rate sensors in different price ranges. The most common type is the piezo electric gyro, there are others but they are very expensive, such as fibre optics gyros and laser gyros. The usages of gyros have quite many benefits. The item itself can be very small and could easily be attached anywhere on the steering wheel, and thus it does not have to affect the driver in any significant way. One of the problems with this system is that it don’t measure just the angular rate of the steering wheel, components of the roll and yaw rate is affecting the signal. No system on the market uses this technology today, however it exist a patent on a quite similar system from South Korea [8]. The patented system seem not to include any compensation against the influence regarding roll and yaw rate. It can exist other patents as Nintendo uses rate sensors in steering wheels on their video game console Wii.
3 Specification of selected system

The decision of which system that is going to be in use is based from the project targets and the systems that is available on the market. None of the existing ready systems are satisfying due to installation problems and the fact that they are affecting the driver. The decision is to develop a complete new system based on the rate gyro technology and make it compatible to the DL2 unit from Race Technology.

The basic idea is to have a piezo electric rate sensor parallel with the steering wheel axle and have another rate sensor mounted somewhere else in the vehicle that register all of the movements of the vehicle body. Both signals from the different gyros are recorded. To get the steering angle the signal from the body fixed reference sensor is subtracted from the steering wheel sensor. The signals are integrated to get the angle from the angular rate sensors.

3.1 System design

To get a functional system, available components on the market are examined. The system can be divided in several subsystems

3.1.1 Angular rate sensors

The new system is based on piezo electric components. It is difficult to find satisfying rate sensors with the high demands that is set by the running conditions. The gyros are all measuring angular rate, and the upper limit for the steering wheel gyro was examined by using data from experiments. The procedure was slalom and double lane change. Some drivers were able to actuate the steering wheel in an angular rate in the region of 1000º/s. The problem is that sensors working in this region are quite expensive and that high speed gyros are terrible to measure angular velocity in low revolution speeds.

As the system is to a prototype the decision is to base the system on a gyro working in the region up to 500º/s. This is done to get the angular velocity in the low speed region as well to cut cost. If the system is shown to work properly in the low speed region the system can be complemented with a high speed gyro in the future.

Figure 11: Systron Donner LCG-50 rate sensor [9]
The gyro chosen is the LCG-50 Rate Sensor from Systron-Donner, see Figure 11. It is inexpensive, compact and can be ordered in a variety of ranges up to 500º/s. A 500º/s gyro is chosen for the steering wheel and a 250º/s gyro is chosen for the reference gyro. See Appendix for specifications of the sensors. The gyros are mounted in small aluminium cases as seen in Figure 12.

![Figure 12: Rate sensor with casing and windshield attachments.](image)

The sensors are connected to DL2 base unit with shielded high flexible cords. There are also two capacitors mounted on the gyro as it should be according to the instructions when you use longer cables.

### 3.1.2 Steering wheel attachment

The gyro is attached to the steering wheel using an aluminium beam with fork ends. Perpendicular to the beam is a hook that holds the gyro attachment rigid. On the beam there is a ball joint that can be fixed in different positions. The ball joint is of the same type as found at digital camera tripods. The ball joint is used to align the gyro with the rotation axle of the steering wheel. See Figure 13.

![Figure 13: Steering wheel attachment.](image)
3.1.3 Windscreen attachment
The reference gyro is attached to the inside of the windscreen with a suction cup equipped with a similar ball joint like the one on the steering wheel, as seen in Figure 14.

3.1.4 Adjustment tool
To get the reference sensor to work as intended it must have the same operating axis as the steering wheel unit. A special tool with two cylinders attached in both ends is used to fix the gyros in the same angle, see Figure 14.
4 Installation and use

The installation of the equipment is straightforward. It can be installed in several ways but the following is an example used as procedure when testing the system.

4.1 Installation procedure

Mount the steering wheel gyro on the double ended fork with the cord facing the driver. Attach the hook and tighten it until the setup is rigid. The gyro case ball joint must not be tightened yet. Find an area that are perpendicular to the steering wheel axle and put a plane straight strip of plate on this, see Figure 15. Attach the windscreen gyro on an appropriate distance from the steering wheel so the adjustment tool can be fitted in both brass holes on the casings. The ball joint on the windscreen sensor must be loose. Use the tool to get the gyros aligned with the plate on the steering wheel. Tighten both ball joints and confirm them being rigid.

Figure 15: Installing the sensors.
4.2 Measurement procedure
When the cables are attached to the DL2 and the unit is on, the measurement procedure is as follows on the present system set-up.

1. Align the steering wheel at an angle as close as possible to the angle of 0° and let go of the steering wheel. Alignment can be done by attaching a piece of steel wire attached to the dash and another one on the steering wheel and align them together. This is done to find the angle 0° as the gyros doesn’t know the starting angle.

2. Start logging data. Don’t touch the wheel for a couple of seconds. This is done to get a good value as possible of the voltage at 0°.

3. Do the driving test procedure as intended.

4. After the test, stop the vehicle. Adjust the steering wheel to the angle of 0° and let go of the steering wheel.

5. Stop logging.

4.3 Retrieving Data
The data has to be analysed and corrected before the actual steering wheel angle is calculated. This is done in different steps. First the desired file is opened with the Race Technology software that is available for free download on the Race Technology homepage, www.race-technology.com [10]. When the program is installed on the computer it is just to double click on the file that is going to be examined.

The raw signals from the sensors are different amplitudes of voltage depending on the rotational direction and speed. The signal must be scaled with a predefined specific scale factor of each sensor. When scaled the signals must be integrated to obtain the input angle at certain time.

To retrieve the steering angles the first thing to do is to open the “Variable manager” in the program, see Figure 16.

![Figure 16: Where to find variable manager [10]](image-url)
The signals from the gyros are in Volts. The sensor signals are found under the “External input” tree. As the cords are connected in the present system the sub tree “analog 11” is the voltage from the steering sensor. The sub tree “analog 12” is the reference sensor. To not get these mixed up they can be renamed to suitable name under the sub trees by clicking the “+”. Make sure that the boxes in front of them are checked, see Figure 17.

Press “Apply” and check the plots under “XY graph” icon on the main view. Press the “Data” button and examine the plots. If the test has been done with a steady state of a zero degree angle at start and end of the run, zoom this area and estimate the average voltage of the steady state, see Figure 18 were the voltage of the steering angle are displayed. This voltage is an input to the next step.
To examine the signals as an angular velocity go back to the “Variable manager” and choose “User defined variables”. Open one of them and start by change the name to prevent a mix up. For the signal of the steering sensor open the “Edit equation” feature under this tree. Fill in an equation using following order:

$\frac{\text{VAR}_0210 - \text{mvz}}{0.0032}$

“VAR_0210” is the signal of the steering sensor in Volts. “VAR_0210” can either be typed directly in the equation editor or picked in the scrolling list regarding variables. The “mvz” in the equation must be replaced with the value of the mean voltage at zero angle, examined when checking out the voltage plot of the steering signal. 0.0032 is a predefined scale factor. Set the unit to $^{\circ}/s$. See Figure 19.
Run the same procedure for the reference signal in another user defined variable. The “mvz” signal will differ and the scale factor is 0.0064. The variable name of the reference sensor is “VAR_0211”.

Open up a third “User defined variable” for calculation of the steering wheel angle. Name it to a suitable name. Open up the “equation editor” and take the steering angular velocity and subtract the angular velocity from the reference sensor. The variable names are found under the variables slider in the equation editor. Set the unit to degrees as seen in Figure 20.
In your “User defined variable” there is an “Advanced option” sub tree. Open it and press “Calculus” then choose to integrate by time. See Figure 21.
Make sure that all the boxes of your variables are checked. Press "Apply" and examine the plots under “XY graph” as seen in Figure 22.

![Figure 22: Plot of steering angle over time [10].](image)

A good plot of the steering angle should be close to zero at the beginning and end. If the signals are not zero check the zero mean voltage at both sensors. Remaining errors can be fixed with an external program such as MatLab [11].

For export to MatLab proceed as follows. The export tool is found under “File”/”Export as Data”. Then choose “Export as *.mat file”. Open the file in MatLab using the following command in an m-file.

```matlab
[filename, pathname] = uigetfile('*.mat','Load data from sensor system');
if filename ~=0
    fil = open([pathname filename]);
end
Data=fil.Data;
Vars=fil.Vars;
```

The variable names are found in Vars and the values of the different variables are found in the Data matrix.

If the fault with a misaligned value of the angle of zero occurred, it can be corrected using the following procedure in MatLab. Make an average of the voltage of the time when the steering wheel was untouched. When new zero voltages are retrieved, use these as input in the Race Technology program.

If the fault still occurs, the scale factor of the reference gyro can be adjusted manually until the alignment results are satisfactory. This is due to the scale factor of the sensors can vary slightly from time to time. Factors that can affect the measurement are temperature changes and variation of supply voltage. A change of the scale factor of ± 0.00001 can solve the misalignment.
4.4 Adjusting results

If it is possible to access a backup system such as the one used in the car of the Vehicle department or another system that can indicate a fixed position on the steering wheel, a curve alignment can be done. The method can be done as followed.

1. Align the curves from the reference system and the KTH system in time by for example make the peaks of the two signal to occur at the same time.
2. Find the value of zero of the reference steering angle signal in time vector. Then plot the angle signal from the KTH system at these times.
3. Use the curve fitting tool cftool in MatLab and make a curve fit to these points at the KTH system. Retrieve the equation for the drifting curvature in cftool. Subtract the curve retrieved from the sensor signal from the steering wheel signal from the KTH system.
5 Results
To estimate how good the new system works a comparison to the old system has be done. The measurement has been done with marked angles for 180° and 360° on the steering wheel. The systems should be as precise as possible for these angles.

5.1 Raw data
When evaluating the raw signal from the two systems the results can look like in Figure 23. In the figure it is shown that adjustments have to be done with both signals to confirm the accuracy.

![Raw data of the steering angle from both systems.](image)

The signal differ in time due to the fact that it is two separate systems started individually. A definite maximum value has been identified in both of the signals, these must occur in the same time and have the same amplitude. The only adjustment done this far is to get the rate sensor signal start at zero. This has been done by subtracting the difference in the beginning of the measurement when the steering wheel was not affected by any movement. The old system shows an error about 10% due to a scale factor error. When correcting the differences that is due to difference in time that the systems is started to measure and the linear error in the old system the curves looks like in Figure 24.
5.2 Correlated data

It now can be noticed that the new system is not consistent at the angle of zero as the old system is. This can be adjusted by using the MatLab curve fitting tool cftool, See chapter 5.4. When correcting the fault of the zero amplitude the result is shown in Figure 25.

![Figure 25: Fitted curves](image)
The only difference remaining between the two measurements shown in Figure 28 is now the inability of the old system to measure angles that exceeds -340°.

### 5.3 Comparison of rate signals

To further compare the signals, the signal from the old system is differentiated and compared to the raw data of the new system. The old system had a noisy signal so before the comparison a Butterworth filter is applied on it. See figure 26.

![Differentiated signals](image)

*Figure 26: Differentiated signals*

The signals have the same behaviours in general, which verifies that the signal from the new KTH system is correct.

### 5.4 Double lane change

For verification of the system performance in real scenario a double lane change test was done, using the same standard (ISO 3888-1:1999) as the ones executed in the course that the new system primarily will be used. In Figures 27, 28 and 29 the results from this test can be seen, driving at the speed 50 km/h.
Figure 27: Raw data 50km/h double lane change.

Figure 28: Correlated data 50km/h double lane change.
5.5 Measurement errors

If the result is not as expected or strange, some factors can make an influence on the signal. It can be for example the sensors being misaligned, the angular velocity exceeding the limitation of the sensor or an integration fault.

5.5.1 Sensor misalignment

When sensor misalignment occurs the result can look good if the test is executed in a way that the driver executes a similar amount of right and left cornering procedures, but when repeating a curve where a roundabout is circulated several times the result is clear. It is of high importance that the reference gyro and steering gyro has the same rotation axes.

5.5.2 Gyro performance

The sensors used in the new system can be used at a greater angular velocity than it is designed for. The design of the prototype system has an upper limit of 500º/s. It is possible to get over that limit in a standard handling routine. In a future design the upper limit should be higher. To investigate the appearance of a signal that exceeds the rate limits the 250º/s sensor was mounted on the steering wheel. The steering wheel was rapidly turned 90º in both direction, after a while the steering wheel was adjusted to zero of a couple of seconds and then later turned 90º in both directions in a more suitable velocity. See figure 30. The first rapid movements results in the signal drifting away and makes the following slower movement to obtain an offset.
5.5.3 Integration error

When the signals from the rate sensors are integrated you always get an integration fault. The fault will be small and will not be seen at all if the signal is corrected in a proper way by adjusting the scale factor or use a curve adjustment to a back up system. A misalignment will appear in the plot of the steering angle as shown in Figure 31.
6 Discussion and conclusions

In this thesis the aim was to develop a suitable steering wheel angle measurement system as the available off-the-shelf products that measure the steering angle does not fulfil all of the requirements set. The major drawbacks are strange driving positions, unavailability of air bags and cost. Different technologies to record the steering angle are studied. The decision fell upon a sensor system constructed with piezo electric rate gyros. It is here shown to be a feasible alternative for measuring the steering wheel angle. The prototype system measures the angular velocity, from which the angle is calculated. There will always be some kind of integration error when trying to retrieve the angles from the signal; this is due to the fact that you always have an offset constant. The new sensor system is adequate for measurement over a short time period such as double lane change and slalom without any modifications. In the regions for the performed studies the system matches the corrected signal from the old system available very well.

The system can be further developed to fit all desired demands. If the measurement system is going to be functional at angular velocities that exceeds 500º/s, a high-range sensor capable of measuring up to 1000º/s can be used in compliment with the now existing low-range sensor. The system would be more user friendly if it was completed with some sort of switch that detects a fixed angle at least once for every steering wheel revolution, preferably at the angle of zero. This signal can be used to adjust the upcoming errors due to integration and the unstable zero voltage done in the same way as adjusting it to the existing old system.
7 Recommendations for future work

The system is a prototype and some of the potential improvements were discovered during the development of the system and other things were discovered when operating. The following things are recommended to improve for an updated system.

An opinion expressed from a Company D test engineer was that if you want to study the general vehicle behaviours and are interested in the steering angles it is sufficient to get this information from the computer network system of the car, the CAN-bus, if it can be used as input in Adams car is not researched. The CAN-bus signal regarding steering differs from different car manufacturers. The accuracy, resolution and signal packaging strategy differ.

7.1 Measurement range

The prototype system is not able to measure angles at higher angular velocities. To make the system more fit for all manoeuvre procedures this improvement is a must. The improvement is costly. Today the limit of the system is 500º/s, in many cases as shown the driver is out of range considering this. The steering wheel attachment must be completed with an additional sensor that can measure at higher angular velocity, up to 1000º/s. However, a higher range rate sensor has a lack of precision in low range, which means that it can not be used alone.

7.2 Angle of zero

The procedure when detecting the angle of zero is complicated with the prototype and lack in precision. A solution for this is to add a position sensor of some kind. The technology that can be used is cheap and straight forward to implement. The sensor can be a position switch that is attached on the dashboard or the steering wheel. It can be a traditional trigger switch that is triggered once per steering revolution. A suitable way this can be done is to have an optical sensor with a transmitter mounted on the top of the dashboard with a ball joint similar to those used on the existing sensors. In this way it can be adjusted so that the ray of this sensor acts together with a reflection tape attached on the outer ring of the steering wheel. The technology described exists and can be bought ready from a variety of different electronic component suppliers.

7.3 Wireless

The basic idea of a full system involves a wireless connection between the equipment mounted on the steering wheel and the base data retrieving unit. The idea is to use an existing technology to do this. After examining the market with Bluetooth, IR and radio waves the latest would do less harm to the signals from the rate sensors due to that fact it wouldn’t be necessary to transform the signal into packages that has to be sent and received between the units. A basic wireless guitar or microphone equipment can be used. However, an attempt of implementing this in the prototype failed due to lack of time and the importance of getting a functional system. The problems occurred when the signal was going to be retrieved at the DL2 unit. A more efficient amplifier unit has to be found or constructed. The technology is functional and the MWL department at KTH has similar solutions in use.
8 References

2. Sensor development Inc., www.sendev.com
5. SAAB Sverige AB, www.saabsverige.com
   KUHMO IND CO. LTD. 2003
11. MatLab 7.1 The MathWorks Inc.
Appendix:
Rate sensor data

LCG50-250

**Power Requirements**
Input Voltage (Nominal) +5.0 Vdc
Input Current <8 mA @ +5.0 Vdc

**Performance**
Standard Ranges ±250°/s
Scale Factor Calibration (at 22°C Typical) 16 mV°/sec ±15% 6.4 mV°/sec ±15%
Scale Factor over Temperature <0.1%/°C <0.1%/°C
Bias Calibration (at 22°C Typical) +2.5 Vdc ± 0.2 Vdc
Bias Variation over Temperature 10°/sec
G Sensitivity (Typical) <0.05°/sec/g
Start-Up Time (Typical) <2 sec
Bandwidth (-3dB)* >50 Hz
Non-Linearity (Typical) % Full Scale Range <0.05%
Output Noise (DC to 100 Hz Typical) <0.005°/s/√Hz <0.006°/s/√Hz

**Temp Sensor**
Scale Factor (Nominal) 6.25 mV/°C
Output Voltage at 0°C +424 mV (Typical)

**Environments**
Operating Temperature -40°C to +85°C
Storage Temperature -55°C to +100°C
Vibration Operating 5 g
Vibration Survival 10 g
Shock 500g PK ½ sine 2 msec
Weight <0.4 oz. [12 grams]

LCG50-500

**Power Requirements**
Input Voltage (Nominal) +5.0 Vdc
Input Current <8 mA @ +5.0 Vdc

**Performance**
Standard Ranges ±500°/s
Scale Factor Calibration (at 22°C Typical) 3.2 mV°/sec ±15%
Scale Factor over Temperature <0.1%/°C
Bias Calibration (at 22°C Typical) +2.5 Vdc ± 0.2 Vdc
Bias Variation over Temperature 20°/sec
G Sensitivity (Typical) <0.05°/sec/g
Start-Up Time (Typical) <2 sec
Bandwidth (-3dB) >50 Hz
Non-Linearity (Typical) % Full Scale Range <0.05%
Output Noise (DC to 100 Hz Typical) <0.01°/s/√Hz

**Temp Sensor**
Scale Factor (Nominal) 6.25 mV/°C
Output Voltage at 0°C +424 mV (Typical)

**Environments**
Operating Temperature -40°C to +85°C
Storage Temperature -55°C to +100°C
Vibration Operating 5 g
Vibration Survival 10 g
Shock 500g PK ½ sine 2 msec
Weight <0.4 oz. [12 grams]