STATE OF THE ART - JAMMER BOX
PIR Vitesco Technologies - INSA Toulouse

February 8, 2021

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Abstract

In this state of the art, we will introduce a new generation of position sensors and explain how they could be integrated in an automative context. The aim is to determine the impact of new sensors on the Jammer Box, Vitesco Technologies' safety test embedded system used to detect and analyse failures from the camshaft and crank position. Physical functioning, implementation and weaknesses will therefore be studied by focusing on two technologies : resolver systems and GMR sensors. We will finally discuss about our contribution to the Jammer Box, from the imagination of new scenarios of signal failures that could occur to the implementation of a SD Card reader to the system.

Keywords
Sensors, Resolver, GMR, SD Card, Automotive

Contents

Introduction

Context

Automotive industry has always been one of the most important witnesses of technological progress. Nowadays, the biggest challenge about the automotive industry seems to be the actual work on autonomous cars and intelligent embedded devices. Such great projects need many systems to work together and exchange data. It is therefore a priority to realize in-depth tests in order to predict every possible behavior. In this report we will not only discuss a product designed for autonomous cars, but a more global tool, aimed to ease the testing process for the entire automotive industry.

Vitesco Technologies has recently developed the Jammer Box [1], a subsystem set up between the car engine and the calculator. This electronic device contains a micro-controller that receives and analyses two incoming signals from the Camshaft and Crank position sensors. The system can then inject some failures into the signals before sending them through the output. The aim is to generate specific anticipated failures so the calculator can deal with them. This process occurs without time interruption, which enables the car to remain a Real Time System despite the adding of new testing features.

The Jammer Box is software-driven by a computer using a USB cable. As a result, it allows the user to send requests and failures to inject from the User Interface.

Two students' teams have been created at INSA Toulouse to help Vitesco develop this box. Some of us will work on new software testing process for the Box, and others will focus on new generations of sensors that could be implemented on the cars in the future.

New position sensors for automotive industry

Our group will be essentially focusing on the hardware part of the Jammer Box. We will use this state of the art to determine how we can adapt the Jammer Box to a new generation of sensors, supposed to be more reliable and more precise [2]. Here, we will only be studying Resolver Technology and Giant Magneto Resistance based sensors. We will try to determine how the Jammer Box can be adapted to a change in the automotive industry to these kind of sensors. With new signals to receive and analyse, potential failures linked to the sensor, a whole of things we will have to add to the code of the Jammer Box, so we this device will still be compatible with next generation of cars.

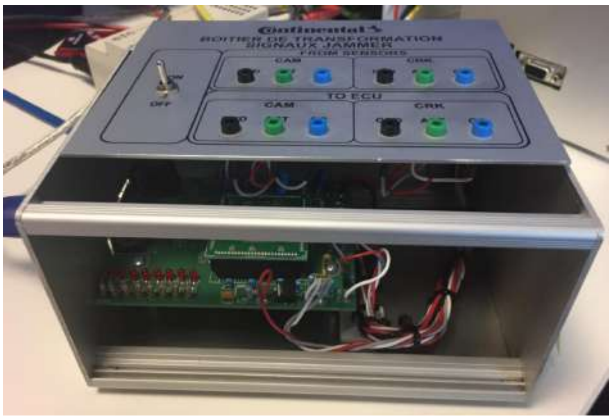

Figure 1: The Actual Jammer Box

Part I - Resolver Sensors

First of all, resolver sensors represent a common and accurate mean of determining angle position and angular velocity. This type of technology is appropriate to an industrial context and more specifically to an automotive application.

1.1 Physical conception

A resolver-type sensor is composed of a rotor (spinning part) and a stator (fixed part), like a motor[3]. The rotor is attached to the rim of the shaft and receives a reference signal (a few kHz). This signal is fed by the stator winding to the rotor winding without contacts, which represents a rotary transformer. Two other additional windings shifted by 90 electric degrees are placed on the stator and provide the outputs named Sine and Cosine signals [4], [5], [6]. As the shaft spins at high speed, we observe an amplitude modulation (AM) on the outputs. The information is obtained within the amplitude of these two signals.

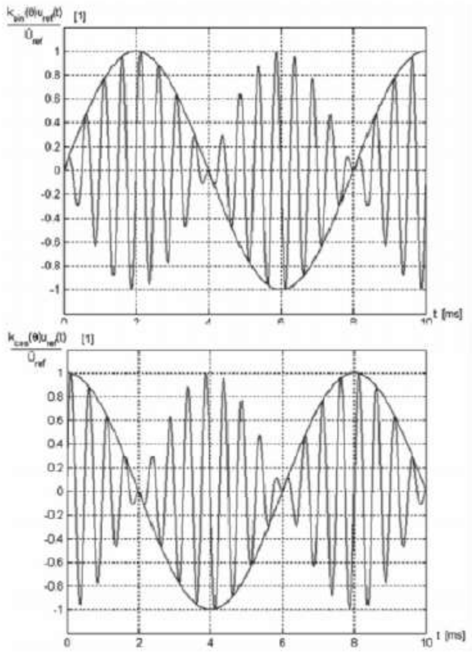

Figure 2: Output signals of a resolver sensor

1.2 Decoding speed and position

If the rotor is excited with a very high frequency in comparison to its speed, the Sine and Cosine signals can be approximated to the following equations :

$$\begin{cases} v_{s1} &= k_e V_e sin(\theta) cos(\omega t) \\ v_{s2} &= k_e V_e cos(\theta) cos(\omega t) \end{cases}$$

with k_e the resolver constant, V_e the amplitude of the rotor voltage, θ the resolver-shaft angle to be decoded, and $cos(\omega t)$ the reference signal fed to the rotor.

Adding a Resolver-to-Digital Converter (RDC) module will now decode θ from these signals. First, as we are dealing with analog signals, the system must feature two Analog/Digital Converters (ADC) in order to interpret the information.

A first Resolver-to-Digital converter solution may consists in utilizing a micro-controller to do the calculation. The ratio $\frac{v_{s1}}{v_{s2}}$ is indeed equal to $tan(\theta)$. By calculating the inverse tangent values or simply storing them on an external memory [7], the shaft angle can be deduced.

However, a more common method is to implement a tracking loop RDC straight after the ADC's [5], [8]. The aim is to feed the angle obtained ϕ back to the resolver outputs signals. In order to compare them, the angle ϕ must be transformed to $sin(\phi)$ and $cos(\phi)$. The reference signal is then fetched to remove the carrier frequency and demodulate the information. This process allows to get the error of measuring. Finally, this error signal go through a low-pass filter and two integrators which return both position and angular speed of the shaft. This tracking loop forces the measuring error to zero and ϕ becomes equal to θ.

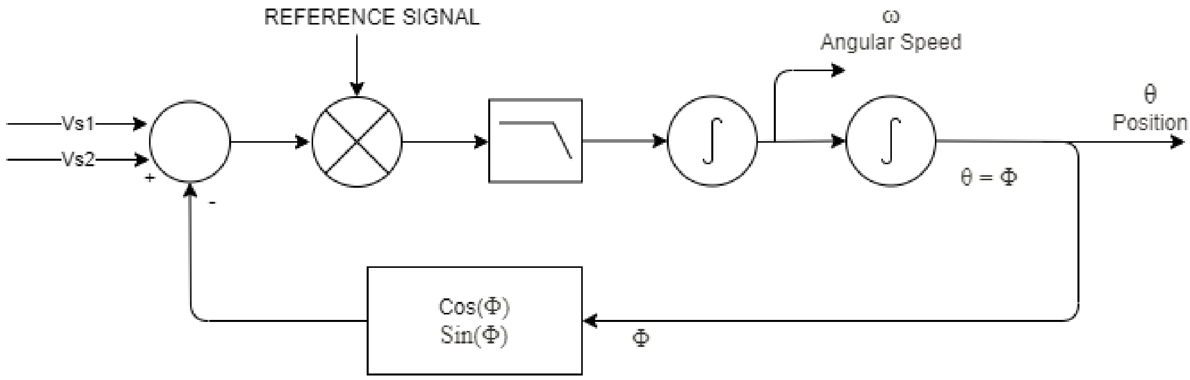

Figure 3: Resolver-to-Digital Converter tracking loop

1.3 Advantages and drawbacks

As it has been said previously, resolver sensors are particularly suited for motor applications. They provide accurate and reliable information even at very high rotational speed. This technology is not especially sensible to vibrations and large temperature ranges and can therefore be integrated into critical environments [7]. Also, they do not need any external coupling device, which makes them appealing in traction applications like electric vehicles [6]. Using a tracking loop as a Resolver-to-Digital converter enhances the precision even more by insuring a null measuring error in most cases [5].

On the other hand, the addition of an additional module to decode the information is required and represents the main drawback of resolvers. Compared to other sensors, the technology is more complicated to use and implement. Considering our application, the Jammer Box micro-controller can not take care of this function, as it must be able to send the signals again without any modification.

The cost of the system can highly fluctuate as well, depending on the RDC solution adopted. The tracking loop solution almost doubles the cost [7]. An alternative way that reduces the cost and preserves accuracy may be magnetic resolvers that uses Hall effect [6].

Furthermore, if the information transport between the resolver and the RDC module is made utilizing wireless means, jamming attack issues must be taken into account an anticipated [9].

1.4 Potential failures

All the advantages and drawbacks presented above have been established considering that perfect outputs signals were fetched to the RDC module. Nonetheless, they can indeed present some failures that can be integrated and reproduced by the Jammer Box to meet safety requirements. Position errors coming from RDC faults will not be discussed here as it does not concern the output signals.

First of all, winding and interconnection faults can happen in the resolver coils resulting in opens or shorts [5]. Additionally, the signals can be deformed as follows.

There can be an amplitude difference between the outputs which means one of the signal equation becomes $(1+\alpha)\cdot k_e V_e cos(\theta) cos(\omega t)$. For instance, an amplitude imbalance of 0.62 % engenders a 1 or 2 LSB accuracy degradation out of a 10 bit resolution [8].

Also, the output can present a phase misalignment, which makes the signals out of phase by not exactly 90 degrees. Consequently, one of the equations becomes $k_e V_e cos(\theta+\alpha) cos(\omega t)$.

Finally, as the stator and rotor coils cannot be perfect inductances, they are likely to contain harmonics. When a single harmonic is present, 0.31 % of the fundamental component is sufficient to produce 1/2 LSB position errors. Considering this, amplitude and phase errors represent the dominant factors and the harmonic distortion becomes less-distinctive.

1.5 Application and use case of this technology

Unlike encoder sensors which provide relative position, resolvers are utilized as absolute position transducers to control position and speed of actuators in many flight critical applications where robustness, accuracy and ability to operate in extreme environmental conditions are required.

They are used in other different harsh environments and extreme applications like into the feedback of servo motors, surface actuators, paper and steel mills for speed and position feedback, control systems of military vehicles, communication position systems, fuel systems of jet engines, production of gas and oil, to determine vector angle and component, to control the amplitude of pulses and pulse resolution [4], [7], [8].

Part II - Giant Magneto Resistance Sensors

Giant Magneto Resistance sensors, GMR, are very accurate magnetic field sensors with exceptional temperature stability [10]. They are sensitive to magnetic field, thus allowing the accurate detection of a ferrous part or magnet. When the GMR sensor is subjected to a magnetic field, the resistance changes greatly (usually 10% to 20%), whereas the maximum sensitivity of other types of magnetic sensors is a few percents.

2.1 Physical Conception

Giant Magneto Resistance sensors are based on the principle of magneto-resistance effect [11]. It refers to the phenomenon implying that the resistivity of magnetic materials changes greatly when there is an external magnetic field compared to when there is no external magnetic field [12]. From the figure, we can see that there are two different layers [13] :

- Fe (in yellow): ferromagnetic layer (arrows indicate the direction of magnetization)
- Cr (in white): non-magnetic layer.

Inside the ferromagnetic layer, the magnetization direction changes with the direction of the external parallel magnetic field. The giant magneto-resistance is determined by the angle between the magnetization direction of the two layers. When the magnetization direction of two ferromagnetic layer are the same, the lowest value will be obtained, while an opposite direction will provoke the highest giant magneto-resistance value.

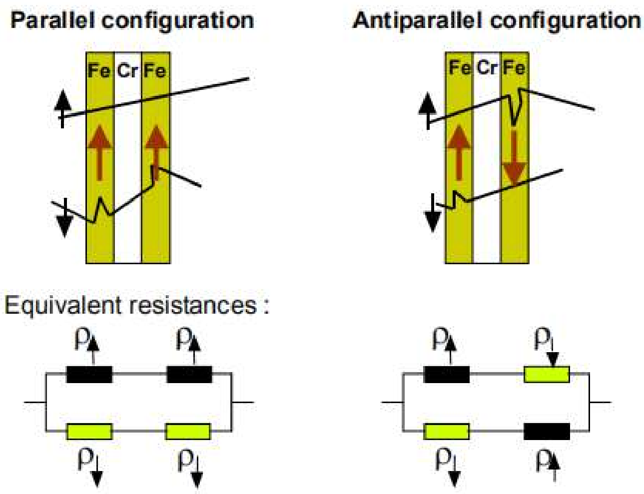

Figure 4: Principle of GMR sensors

2.2 Advantages and drawbacks

GMR sensors offer several advantages : At first, they provide contactless measurements, and consequently wear-free measurements, of mechanical quantities. All magnetic sensors have this advantage, so it is also one of the characteristics of GMR sensors, such as measuring rotation angle and angular velocity [14].

Furthermore, they are very sensitive and very accurate [15]. For instance, they are able to store data through direction of magnetization and read data through output current. In addition, they can output enough current in a small magnetic field. According to experimental results of durability and performance tests, we can deduce that GMR sensors have high durability for high temperature. Indeed, they can withstand 300 hours at 200 degrees Celsius besides a wide margin until 200 degrees Celsius. Additionally, GMR sensors are efficient within larger working distances. Finally their cost is usually low, about the same price as other sensors, or even lower. Some factories can use inexpensive magnetic materials to manufacture GMR sensors, such as ferromagnetic materials, to reduce costs.

Therefore, GMR sensors are currently one of the most high-performance devices and can then replace Magnetoresistive sensors. Yet some important drawbacks remain, such as non-linearity, hysteresis and temperature-dependent output[16]. All these disadvantages can reduce the accuracy of the practical measurements [17].

2.3 Potential failures

Firstly, the operation of GMR sensors demand certain requirements about the magnetic field intensity. Therefore, the sensor magnet should provide a sufficiently strong magnetic field in the designated air gap. A magnetic field strength that is too large or too weak will produce additional angular deviations. A low field strength cannot drive the magnetization direction of the free layer to be aligned with the external magnetic field, whereas a too strong field strength will affect the magnetization direction of the reference layer.

Secondly, as they are active devices, GMR sensors have requirements for the power supply stability. If an over-voltage power supply is utilized, its accuracy will be directly affected.

2.4 Application and use case of this technology

Because of its high durability and sensing performance, GMR sensors can be applied to detect linear or rotational motion, linear or rotational position and speed in automotive systems [18], for example:

- Position of Pneumatic Cylinders
- Speed and Position of Bearings
- Speed and Position of Electric Motor Shafts
- Wheel Speed Sensing for ABS Brake Applications
- Transmission Gear Speed Sensing for Shift Control
- Position Sensing for Shock Absorber Feedback Control

Furthermore, as GMR sensors are able to store and read data through direction of magnetization output current, they represent an ideal choice for making Hard Disk drives. They can also output enough current in a small magnetic field, therefore, compared with other storage bodies, the data density of storage is greatly improved.

Part III - Our contribution to the Jammer Box

As presented in the introduction, we are going to work on the real Jammer Box to add new features and enable Vitesco to keep the system compatible with new generations of cars.

3.1 Consideration of new failures due to the implementation of new sensors on cars

As we have seen before, the automotive industry could switch to these new kind of sensors: GMR and Resolver. We now know that the Resolver technology is more common in the context of electric cars. The sensor would not be that efficient in a thermal car. GMR Sensors will be preferred for the classical automotive industry. Now we have to wonder how to take into account the new failures coming with these sensors.

The Resolver sensors present some new failures that have been stated previously. Most of them can be incorporated to the Jammer Box process easily. Shorts and opens can be implemented in the same way that it has been done before. Then, by using the micro-controller already present, adding constants and gain factors numerically to simulate offset and amplitude errors can be done without difficulties.

However, introducing phase and harmonics errors seems to be more intricate. The signals equations must be known in order to create a difference. Thus, a sine or cosine can be calculated in parallel and added to the original signal. This will automatically induce some delay as the calculation is more complex. As a consequence, implementing these errors by using analog means might be a good solution to avoid this issue. In this case, the internal structure of the Jammer Box will have to be changed.

Concerning the GMR sensors, the main problems we might face are linked to the environment of the sensor, and its power supply. Indeed, the magnetic environment has a real impact on the correct polarization of the reference layer. And as the output signal is a direct consequence of this polarization, we must be sure that the magnetic field reference close to the sensor is well known. This could enable us to choose the right settings on the Jammer Box interface and digitally compensate the signal alteration due to the magnetic field.

We know that the output signals of GMR sensors are similar to those of the classical sensors used with the Jammer Box currently. It is comparable to a Pulse Width Modulation signal in the case of an angular position measure. Therefore, the system failures signals generated by the Box and the ones already implemented will be alike. We will have to determine the different characteristics of these signals and assign them to the errors again like EveCamScgGMR [1] for example.

3.2 SD Card implementation and Data Saving

The last intern who worked on the Box added a SD Card reader to the board. This has been done so that we can save the signals received from the sensors and play them later on. In addition, scenarios of injected failures could be played again without having the motor connected to the calculator. The idea of data saving remains the same between a USB drive and a SD Card [19]. Our contribution to this feature will be to create the whole program necessary to drive the SD Card slot. That will enable the DS PIC micro-controller to save the data it receives from the sensors on the SD Slot. The last intern set up the whole system. The new electronic design is shown below.

[1] Already existing error in the Jammer Box data base

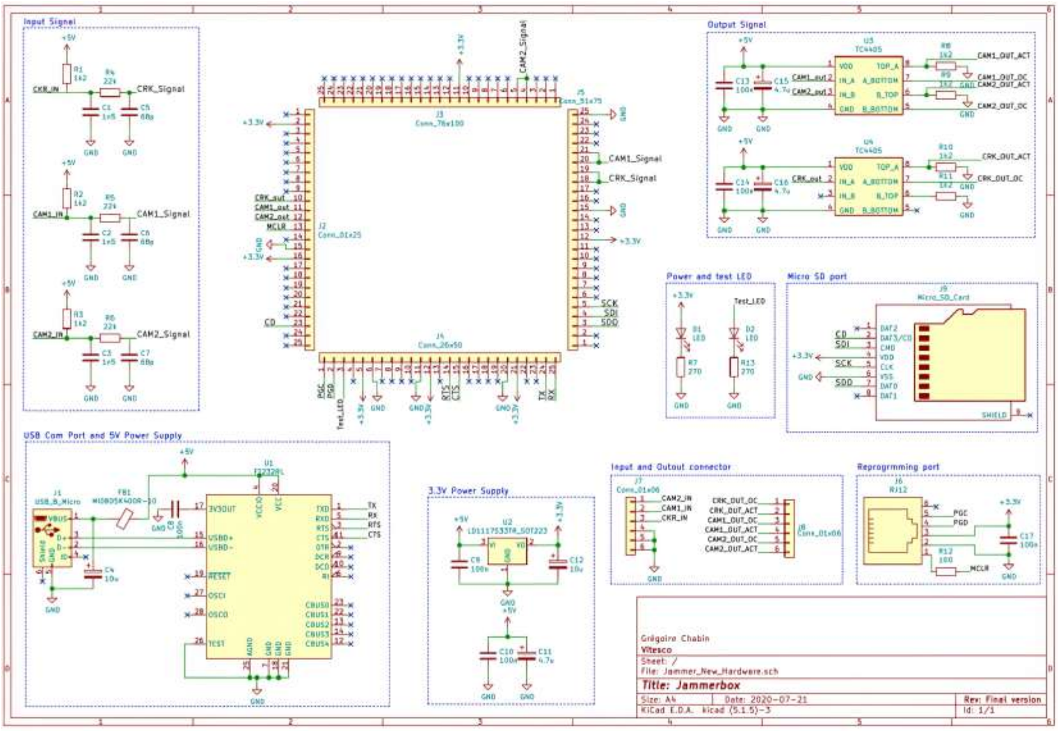

Figure 5: Electronic schematic of the Jammer Box

The SD Slot is located on the right of the schematic. The way to connect every pin has already been studied by the intern. What we will have to do is to create a new extension, proper to Vitesco, that will be used to save and read the files in order to play a signal again.

The concept is to get the different signals from the sensors and immediately save the incoming data to the connected SD Card. All the data read and write process will be possible thanks to six main signals [20] :

- System Clock : Necessary to sync both the DS PIC Micro controler and the SD Slot
- SDI and SDO : Pins to read or write the connected SD Card
- GND and 3.3V : Pins to power the component
- CD : Boolean signal returning a True value - 3.3 V - if a card is present

The logic consists in receiving the different signals from the sensors. Then with an appropriate software program, we will on the one hand edit the signals and send them through the output, and on the other hand write them on the SD Card. All this behaviour will be used into a global function to drive the SD Slot, from the detection of an SD Card, to the extraction of this one.

The implementation of this SD Slot will enable us to link the two parts of this research project. Indeed, the hardware team will have to create the driver of the SD Card reader, so that the other team can save the results of tests on the Card. That will imply the creation of a file format understood by the Jammer Box, a whole of function easy-to-use so that the software team is able to quickly write on the SD Card and add new files.

3.3 What if we could know if we receive fake information from the sensor ? An opening to security

Industry is nowadays highly subjected to rules and obligations about maximum authorized speed, chemicals elements for the painting... One of these rules recently revealed Volkswagen was faking his carbon output so that their car could pass the different compliance tests. The fact is that they artificially reduced their gas emanation. We could maybe work on a new kind of detection for the Jammer Box, linked to the gas sensor. Knowing the response of a sensor to a gaz, we could try to detect if there is any abnormal signal inserted by the constructor.

We could extend this idea to other signals coming from other devices of the car, and try to detect all kinds of malicious signals. For instance, it could be the detection of a fake signal hiding a non respect of the rules, like it happened in the Volkswagen case. That would make the Jammer Box a complete test system, ready to face either failures or malicious information.

Conclusion

Thanks to this state of the art, we could determine the different features of the next generation of sensors supposed to be used in the automotive industry. Both of the GMR and Resolver technologies represent a good advance on the reliability of sensors. Indeed, we must know that most of the sensors used today are optical. That means they can get wrong information much easily compared to a magnetic or electromagnetic wave based detection. We assume that these new sensors will not become the principals in the industry overnight. So, we will not make the Jammer Box to a GMR/Resolver dedicated device. We will just add the ability to the system to deal with these new kind of signals. With all this research, we will be able to make various tests to implement the new responses of the sensor. We will now focus on the realization of all those tests, identify the typical signals coming for designated failures, and include them to the Jammer Box.

Once we will have the typical response of the sensors, we we will be able to focus on the implementation of the new code to save the signals coming from the sensors directly on the SD Card in a proprietary file format. This will enable the box to play the different signals at any time to ease the testing process.

Finally, we will probably try to imagine new scenarios that could help detect fake signals edited by constructors to pass the conformity tests for example. That would also imply adding new inputs to the Jammer Box. Indeed, for the moment, the system is only connected to the cam and the crank position sensors. But we could easily imagine adding a pin that could be connected to the gas emanation sensors or the fuel sensor. Car constructors could fake the CO_2 emanation of the car, or lie on the fuel consumption at the time of official tests. Our role could be to help official organizations determining if a constructor is trying to improve artificially the performance of their product.

But first and foremost, our main focus will be to implement the SD Card driver to the software so that our two teams will be able to collaborate on an improved and enhanced version of Vitesco Technologies' Jammer Box.

List of Figures

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