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STUDY ON VIRTUAL SENSORS AND THEIR AUTOMOTIVE APPLICATIONS

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Abstract: *Currently, the automobiles are electronically controlled. Equally, onboard informatics has grown considerably. Therefore, the number of sensors experienced a significant increase. In front of this costly sensory inflation, the development of virtual sensors was generalized. Virtual sensor is about replacing a physical sensor with a software installed in the electronic control unit. The purpose is to obtain the desired information in the absence of a physical part. Tires, engines, cabin, many vehicle parts are riddled by those virtual sensors. Most often, it is about the replacement of an expensive physical sensor, cumbersome and subject to severe operating conditions which reduces the reliability and increases the cost. Within this context, this article aims a review of the state-of-the-art in the virtual sensors existing in automobiles. Key words: virtual sensor, legislation, monitoring system.*

Keywords: automotive; virtual sensors.

INTRODUCTION

Because of the large number of consumers involved, and hence the economic significance of the entire supply chain, the automobile is the symbol of modern-era Homo sapiens. Historically, the automotive industry was not a major user of advanced controls, but the situation began to change several decades ago with the advent of cheaper, smaller, and better embedded processors and other developments. Today control is pervasive in automobiles, and all major manufacturers and many of their suppliers have invested significantly in Ph.D.-level control engineers. Indeed, over the last decade or more, the automotive industry has become one of the foremost industry sectors in terms of the importance accorded to advanced control technology [7].
To associate a program to one sensor allows calculation of one or more variables necessary to perform an action, such as: regulation of temperature, engine optimization. In ten years, the onboard informatics has developed considerably. According to paper [1], program size has been multiplied by 15. At the same time, the number of sensors also experienced significant growth. After the worldwide downturn and crisis in 2008 and 2009, the automotive market worldwide has bounced back and recovered well. In 2012, approximately 75 million new light vehicles (cars and light trucks) were shipped worldwide. This number is projected to reach 110 million by 2020. Currently, each vehicle has an average of 60-100 sensors on board. Because cars are rapidly getting “smarter” the number of sensors is projected to reach as many as 200 sensors per car. These numbers translate to approximately 22 billion sensors used in the automotive industry per year by 2020 [5]. In front of this expensive sensory inflation and considering the means of computing increasingly stronger, sensor development program type was generalized. Multiplex data allows now different computers to recover easily all the data measured by the sensors. Tires, engine, vehicle interior, etc., all parts are now "riddled" by these virtual sensors.
The development of program type or virtual sensors responds to very different considerations. Most often, it is about the replacement of an expensive sensor, burdensome and subject to severe conditions of use, which reduces its reliability. The principle of a virtual sensor is simple. Starting from the

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measure of useful variables provided by physical sensors, the observer will calculate, reconstruct the variable that seeks to estimate. This calculation is based on mathematical models or, for nonlinear phenomena, on maps. The time scale is of order of hundreds of milliseconds. Computation time must be very fine in order to provide a real-time control of flown bodies. Modeling physical phenomena remain easy to achieve. But nothing compares with simulation modeling operated during vehicles development, where most of the physical phenomena are accurately modeled and simulated.

VIRTUAL SENSORS AND THEIR APPLICATION

Comfort. Conditioning systems are becoming more prevalent. To ensure thermal comfort of passengers, the control system pilots different actuators, such as throttle actuator airflow. The regulation it is made starting from one measure taken by an onboard air temperature sensor, located inside the passenger compartment. This solution has two disadvantages: on the one hand, sensor failure causes total loss of control regulation, and on the other hand, will be expensive to place multiple sensors to estimate the temperature at several points of the vehicle. Adjustment is made starting from a single value, without considering the rear passenger comfort, for example (Figure 1).

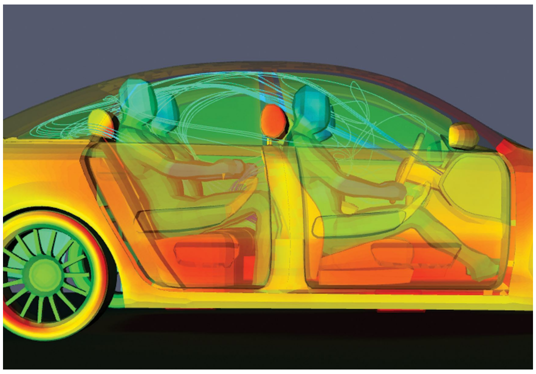

Figure 1. Thermal comfort of passengers

PSA Peugeot Citroen has developed a modeling program that replaces the thermal sensor [1]. This solution allows to reduce costs, increases system reliability and especially, improves performance control by estimating temperature over the whole cabin. Modeling will be based on outside temperature information, one sunny sensor and on an interior modeling, in relation to a given vehicle (it takes into account the interior materials and human beings). System initialization is based on the latest information calculated, the last stop of the vehicle, outside temperature and the sunshine phenomena. On strong heat and after a long stop, the system will be initialized taking into account the external temperature corrected by the effect of sunshine phenomena. In the case of strong cold, the system calculates the thermal losses in the cockpit in order to regulate air conditioning. The observer program is now on installed on all new vehicles of PSA [1].
Traditional vehicle cabin climate control systems attempt to regulate the temperature and humidity for the cabin environment as a whole to a setpoint. Cabin Comfort Control (C-Cubed) focuses on first identifying the comfort or thermal sensation experienced by the driver and passengers and controlling the heating, ventilation and air-conditioning (HVAC) to ensure that this is neutral [3]. "Neutral" thermal sensation occurs when the occupant is neither too hot nor too cold. This revised aim might be achieved using less energy than traditional climate control systems since: comfort may be achieved over a range of temperatures and thus it is not always necessary to tightly regulate the cabin environment to a particular set point, temperature and humidity control can be focused on the driver and passenger, comfort tends to be context dependent (e.g. lower temperatures might be acceptable in winter when passengers are already dressed for a cold environment; conversely, higher than usual temperatures might be acceptable (and even preferred) in a hot climate), natural ventilation can be preferred where the external environment allows. The development of the C-Cubed approach is based on the following method [3]:

- virtual sensors "measure"/estimate the occupant's skin temperature / humidity at several locations. The sensors are virtual in the sense that estimates are made based on real sensors placed around the car cabin. A key goal for this work is to identify the optimum set of real sensor positions to maximize the quality of the estimate for all virtual sensors. The estimators are derived using machine learning based on empirical trials with real sensors used in the virtual sensor locations;

- the "state" of the environment is derived based on a combination of real and virtual sensors;
- a reinforcement learning (RL) algorithm is used to train the system to adjust set-points to reduce HVAC energy consumption while maintaining comfort;
- embedding the RL algorithm into the car means that the HVAC control can gradually learn user preferences. Potentially, different preferences can be learnt depending on who is driving (say, by recognizing the key). The RL system will learn preferences by trying to reduce instances of user intervention (where the user turns a dial to increase or reduce the temperature) [3].

Tire pressure monitoring system (TPMS). From 1st November 2012, all new-type vehicles will be required by EU law to have a pressure based tire pressure monitoring system installed. This applies to the road wheels, not the spare. By November 2014, all new passenger vehicles will have to have TPMS installed by the manufacturer. The law is not currently retrospective, and does not apply to older vehicles. This law applies to passenger vehicles only, with no more than 7 seats [9]. TPMS is an electronic system designed to monitor the air pressure inside the pneumatic tires on various types of vehicles. TPMS report real-time tire-pressure information to the driver of the vehicle, either via a gauge, a pictogram display, or a simple low-pressure warning light. TPMS can be divided into two different types: direct (dTPMS) and indirect (iTPMS).

The significant advantages of TPMS are summarized as follows:

- fuel savings: according to the GITI (global tire company which is offering a complete range of quality tires and services) for every 10% of under-inflation on each tire on a vehicle, a 1% reduction in fuel economy will occur. In the United States alone, the Department of Transportation estimates that under inflated tires waste 2 billion US gallons (7,600,000 m3) of fuel each year [12];
- extended tire life: under-inflated tires are the #1 cause of tire failure and contribute to tire disintegration, heat buildup, ply separation and sidewall/casing breakdowns;
- decreased downtime and maintenance: under-inflated tires lead to costly hours of downtime and maintenance
- improved safety: under-inflated tires lead to tread separation and tire failure, resulting in 40,000 accidents, 33,000 injuries and over 650 deaths per year. Further, tires properly inflated add greater stability, handling and braking efficiencies and provide greater safety for the driver, the vehicle, the loads and others on the road;
- environmental efficiency: under-inflated tires, as estimated by the Department of Transportation, release over 57.5 billion pounds of unnecessary carbon-monoxide pollutants into the atmosphere each year in the United States alone [12].

The traditional method of evaluating tire pressure is based on its direct measurement with sensors disposed inside of tires room air, (fig. 2). This method is judged by the manufacturer to be expensive and less reliable. Computer compares pressures measured with predetermined values stored in its memory. The change decided by the user can then put calibration problems and that leads to the appearance of false alerts.

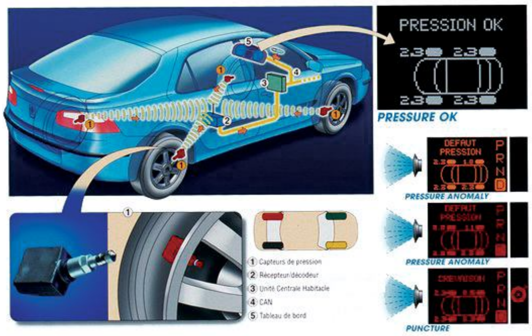

Figure 2. Direct Tire Pressure Monitoring System (dTPMS) [1].

Indirect Tire Pressure Monitoring System (iTPMS). Indirect TPMS do not use physical pressure sensors but estimate air pressures by monitoring individual wheel rotational speeds and other signals available outside of the tire itself. First generation iTPMS systems utilize the effect that an under-inflated tire has a slightly smaller diameter than a correctly inflated one, which means higher angular velocity at the same vehicle speed. These differences are measurable through the wheel speed sensors of ABS/ESC systems. Second generation iTPMS can also detect simultaneous under-inflation in up to all four tires using spectrum analysis of individual wheels, which can be realized in software using advanced signal processing techniques. Current iTPMS consist of software modules being integrated into the ABS/ESC units. With this breakthrough, meeting the legal requirements is possible also with iTPMS such as the Tire Pressure Indicator by NIRA Dynamics AB (Swedish company focusing on research and development of signal processing and control systems for the automotive industry) [13]. TPI by NIRA was the first iTPMS to comply with the United States regulation FMVSS 138, as it was released with the Audi A6 for the 2009 model year. Since then, it has been introduced in various VW and Audi models and is in use in the United States in more than 250,000 vehicles. iTPMS cannot measure or display absolute pressure values, they are relative by nature and have to be reset by the driver once the tires are checked and all pressures adjusted correctly. The reset is normally done either by a physical button or in a menu of the on-board computer. iTPMS are, compared to dTPMS, more sensitive to the influences of different tires and external influences like road surfaces and driving speed or style. The reset procedure, followed by an automatic learning phase of typically 20 to 60 minutes of driving under which the iTPMS learns and stores the reference parameters before it becomes fully active, cancels out many, but not all of these. As iTPMS do not involve any additional hardware, spare parts, electronic or toxic waste as well as service whatsoever (beyond the regular reset), they are regarded as easy to handle and very customer friendly [13].
Due to the significant influence tire pressure has on vehicle safety and efficiency, TPMS was first adopted widely by the European market as an optional feature for luxury passenger vehicles in the 1980s. The first passenger vehicle to adopt tire-pressure monitoring (TPM) was the Porsche 959 in 1986, using a hollow spoke wheel system developed by PSK (Porsche-Steuer Kupplung). In 1996 Renault used the Michelin PAX system for the Scenic and in 1999 the PSA Peugeot Citroën decided to adopt TPM as a standard feature on the Peugeot 607. The following year (2000), Renault launched the Laguna II, the first high volume mid-size passenger vehicle in the world to be equipped with TPM as a standard feature.
In recent years, several advancements have been made in the TPMS market. New developments aim at battery-less systems, such as those developed by VisiTyre TPMS, and advanced iTPMS [11]. STE Engineering [10], has introduced an energy efficient wireless sensor device based on a technology called SPX (Short Pulse Technology) which integrates a hybrid ceramic circuit inside the body of a standard tire stem. Anyway, these dTPMS advancements have not led to series applications as many practical aspects have not been solved yet.
Example of enabling a virtual sensor of iTPMS. With the aid of a diagnostic program it can be performed the enabling of the tire pressure monitoring system on an Audi A4 B8. The activation of virtual sensor is made at the level of ABS module and also on the instrument cluster of the vehicle (Figure 3). After the activation of the monitoring system, the teaching/training process must be done. The teaching process is performed once after the set key is pressed for the low tire pressure indicator. During the next trip, the control unit saves the measured wheel speeds and the vibration characteristics of the wheels in various vehicle operating states. The vehicle operating states are basically defined by the following parameters: vehicle speed, steering angle, transverse acceleration and yaw velocity. These teaching values subsequently make up the target data which is used for monitoring. After approximately 10 minutes of driving, it is already possible to detect a breakdown (rapid loss of pressure). Approximately 60 minutes of driving are required to detect diffusion loss (slow loss of pressure).
Testing the TPMS system: simply lower tire pressure and take the car for a drive. It should detect the change within a few kilometres.

Figure 3. Enabling the TPMS on the ABS module (Audi A4 B8)

The powertrain. Engine control system is one predominantly system of modern vehicles. The weakness of driving vehicles is the need to provide the necessary power taking into account constraints always ascending: environment, safety, comfort, reliability. Due to these constraints, the trend is to have a more and more precise control, meaning a higher number of sensors on the powertrain. Certainly, this may lead to an increased cost, which could influence the sales volume. Therefore, the idea is to have the best performance to cost ratio. This is why virtual sensors technology has grown significantly. Subsequently, short examples about virtual sensors applied on powertrains will be given.

Detection of the right moment for the injection in the absence of camshaft position sensor. To pilot injection, the engine control must be aware of each piston’s position. As well known, an engine cycle corresponds to four strokes of the piston (intake, compression, expansion and exhaust) and two crankshaft revolutions. In the case of engine control of traditional engines, the engine speed sensor measures the speed at the crankshaft. By using 60 teeth out of which one is missing, the engine control is able to increment during the engine cycle with a step of 60 CA and to detect one piston’s TDC position. The crankshaft configuration being known, all other pistons’ positions are known, too. For instance, for a 4 cylinders inline engine, when piston #1 is at TDC position, then piston #4 is at its TDC, too and pistons #2 and #3 are at their corresponding BDC. The question now is: which of the 2 pistons at TDC is at the beginning of intake stroke? So, the crankshaft position sensor provides information that does not allow knowing if the piston is at the right position for injection and/or ignition. For raising the ambiguity, a second sensor placed on the camshaft may be used.

For simple port-fuel injected (PFI) gasoline engines (without variable valve actuation and/or gasoline direct injection), Renault, for example, preferred to replace this sensor for camshaft position through a solution of virtual program.

In a very straightforward description, for the simple 4 cylinders inline PFI engine, it’s about the following strategy:

- the crankshaft configuration corresponding to 2 by 2 pistons in phase, when trying to start the engine, the injections will be produced for all cylinders; at the beginning for the 2 cylinders whose pistons are at TDC and then to the other 2 (or vice versa)
- this means the engine will receive the necessary fuel so that to be able to start;
- however, even if the engine is now running, the ECU still does not know which of the 2 phased pistons is at the beginning of the intake stroke (for instance); simply, the ECU is not being able to discern;
- in order to solve this problem out, the next logical step will be to stop the injection at one of the 2 phased pistons;
- if the injection was stopped at the right cylinder (defined as the one situated at the beginning of the intake stroke), then the following cycle will be a misfire cycle or a lost cycle;
- this will be seen in the instantaneous angular velocity of the crankshaft, which will slightly decrease;
- in this case, the ECU may draw the conclusion that the injection was stopped at the right cylinder;

- all it has to do to confirm this is to activate the injection at the right cylinder and to stop it at its phased piston's cylinder;
- certainly, this time the crankshaft will suffer a slight increase of angular velocity, giving now the possibility to the ECU to confirm the previous assumptions, i.e. the right cylinder is now known;
- if one piston's position is completely known on the engine cycle, then the others positions are also known (the crankshaft configuration being known).

For direct injected engine (spark or compression ignited), a camshaft position sensor is required in order to avoid this "guessing" strategy which in this case would generate losing fuel when injecting at the end of exhaust strokes. However, this "guessing" logic may as well be applied for this kind of engine, too, but only if the so-called degraded/limp home mode is activated. This can happen if the ECU receives malfunction information from the camshaft position sensor. In this case, the main goal is to be still able to start the engine no matter what.

The mass airflow meter (MAF). To measure the air mass entering the engine, the traditional solution is to use a flow meter. But implantation of the sensor is sometimes difficult due to the numerous constraints. For instance, the MAF should be placed in a long line, straight enough to not disturb the measurement of the effects of flow. Adding this to the MAF's price gives a good reason to implement a virtual sensor. For instance, Renault has also chosen to develop a virtual sensor in order to estimate the airflow rate. Starting from the intake manifold absolute pressure (MAP), air temperature and engine speed, a rather simple semi-empiric modeling of the flow based on the thermodynamic state equation allows the reconstitution of MAF information, Figure 4 [2].

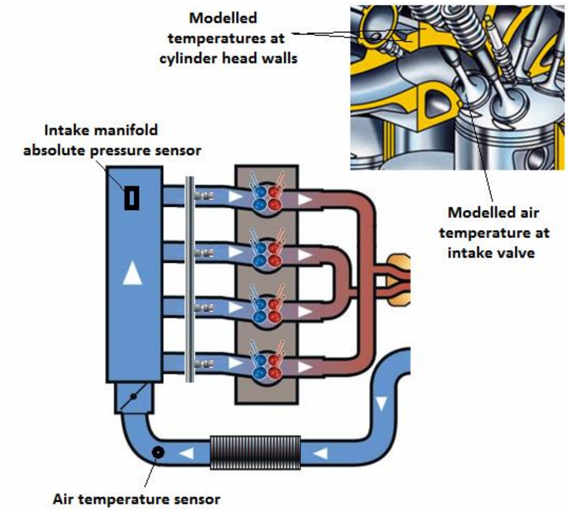

Figure 4. The reconstitution of MAF information

CONCLUSION

The list of new methods successfully developed in the automotive control field goes from hierarchical control structure (distributed on various layers) to gain-scheduled PIDs, passing through artificial intelligence control schemes such as neural networks and fuzzy-logic-based controls (to represent experts' knowledge) [7]. Virtual sensors (that is, subsystems and/or algorithms that exploit mathematical models to estimate process variables or operating conditions) play a large part in this scenario. Virtual sensors are widely used because they are cheaper and more reliable than real ones (which often may not be physically feasible) and can have faster response compared to physical sensing devices.

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