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Capacitive silicon MEMS based combined accelerometer and gyroscope sensors in headlight levelling systems

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Abstract

When driving in conditions with suboptimal lighting, the use of headlights is essential for safe travel. However, headlights pose a fundamental safety conflict as with increasing headlight intensity, visibility is improved, but this simultaneously increases the glaring effect on pedestrians and oncoming traffic, reducing overall safety. To address this issue, the UN has launched a regulation binding all original equipment manufacturers, or OEMs, of the concurring regions to implement automatic head light levelling systems that aim to keep the headlight alignment optimal. The regulation will apply to all new type approvals starting from September 2026 and all vehicles starting from September 2029. Since in most cases OEMs are offering a great variety of different automobiles, this regulation is putting high pressure to find a general cost-effective solution that works for every model and configuration.

When switching from manual headlight alignment to automatic, the system needs to consider how load from passengers and luggage is tilting the vehicle and what is the vehicle pose in respect to the road angle. In static situations, this can be handled with a 3-axis accelerometer sensor in combination with an extended Kalman filter. When adjustment in dynamic situations is required, the complexity of algorithms between sensor data and actuators controlling the headlight alignment becomes significantly higher. The system needs to now take into account accelerations, breaking, driving in bends and vibration effects. To improve interpretation of these dynamic situations, a 3-axis gyroscope must be implemented to the system as well. Additionally, in dynamic situations, a fast response time is crucial and when considering the relatively small angles of adjustments needed, effects of lifetime degradation start to play are role in accuracy. This means that high reliability and performance of the measurement capability is needed for the whole system to retain its accuracy.

Development in the MEMS field has enabled manufacturing of low cost, but extremely accurate, stable and reliable accelerometers and gyroscopes, which makes them a good candidate to address the aforementioned problems. This paper is reviewing an automatic headlight levelling solution utilizing a combined accelerometer and gyroscope sensor, which is based on capacitive silicon MEMS technology.

Index Terms: *Headlight levelling, MEMS Sensor*

Abbreviations

MEMS	Micro-Electro Mechanical System
OEM	Original Equipment Manufacturer
UN	United Nations

1 Introduction

Higher intensity lightning provides better visibility, but when it comes to automotive headlights, this creates a safety conflict, as pedestrians and on-coming traffic are easily blinded by the headlight beams, which in turn poses a safety hazard. This has been the key problem the development in this field has revolved around in recent history and has also led to the launch of a UN induced headlight levelling regulation change. This article provides an overview of said regulation change, basic problems related to headlight levelling and a cost-effective MEMS sensor-based solution.

2 Effect of headlight levelling regulation change

The fundamental safety conflict has also been recognized by the United Nations UN Regulation No. 48 (Installation of Lighting and Light-Signaling Devices). New regulation is being prepared towards safer automotive lighting. The regulation will bind OEMs of the concurring regions to implement automatic head light levelling systems to all new vehicles. The requirement will be enforced in most of the major countries and will apply to all ordinary vehicles and light commercial vehicles. Current latest schedule applies for new type approvals starting from September 2026 and all vehicles from September 2029. [1]. In Europe alone close to 18 million new cars are expected to be produced in the year 2026 [2], divided to a vast variety of different models and since the regulation applies to them all, there is risk that development and implementation costs will become significant. To tackle this, OEMs need to find a general approach covering different models and their different configurations, like wheel sizes and headlight types.

3 MEMS based sensors

Microelectromechanical System, or MEMS based sensors are common in automotive use. Pressure sensors, microphones and airbag crash sensors are all manufactured with processes similar to semiconductor manufacturing. This article is focusing on inertial sensors, and specifically acceleration sensors, or accelerometers and angular velocity sensors, commonly known as gyroscopes. MEMS sensors are widely used in consumer electronics like smart phones due to their small size, low power consumption and high accuracy. The possibility to produce in high volume allows also for low unit prices. The use in the automotive industry sets many additional requirements related to e.g. reliability and functional safety, preventing the use of consumer grade products and designs and adds cost to the sensors.

Acceleration sensors, as the name suggests, are used to measure the change of velocity or static pose. Accelerometers measuring angles in static conditions are called inclinometers. Typical structures used in automotive are based on capacitive sensing principle, effectively measuring the distance of two conductive structures. The benefit of this measurement principle is that it can be used to measure true static acceleration, earth gravity. Figure *1* represents a cross-section view of a simple single-mass 1-axis accelerometer. The mass is connected with a silicon spring structure. Acceleration induces vertical movement to the mass, which changes capacitances C1 and C2. This change is differentially detected by the application specific integrated circuit and converted to a voltage, proportional to the applied acceleration.

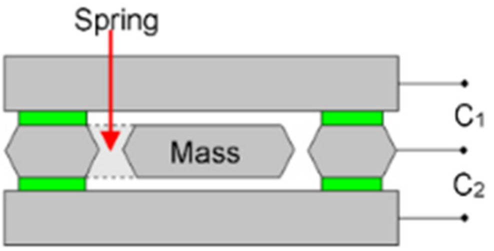

Figure 1 Example cross-section of a single mass accelerometer [3]

In the automotive field, MEMS based accelerometers, have a wide range of applications, including airbag deployment, vehicle stability control, transmission control and headlight levelling. The use as an IMU plays also a key role in autonomous driving applications. This article will focus on the headlight levelling application.

Gyroscopes are measuring rotational motion. As with the accelerometers, typically their measurement principle relies also on detecting change in capacitance. Unlike the accelerometers, in which the change in capacitance is caused by moving masses, the sensing structure of gyroscopes used in the automotive industry usually are of force feedback type. This means that they comprise of vibrating masses held in place by electrostatic forces. The angular rotation experienced by the gyroscope induces Coriolis forces on the gyroscope masses, which act to displace them from null position. Capacitive structures are used to detect this displacement and a voltage adjusted force is applied to compensate this movement and hold the gyroscope masses in place. The adjustment voltage can then be transformed into accurate angular rate information. The measurement unit is usually Degrees per Second.

The moving structure of a single axis force feedback gyroscope is presented in Figure *2*. In this example structure, the angular velocity to be measured is around the Z-axis. The rotation movement around Z-axis causes change of capacitance in the detection electrode system on Y-axis. The driving electrodes on X-axis induce vibration to the proof mass by voltage applied electrostatic force. This force is then used for movement compensation.

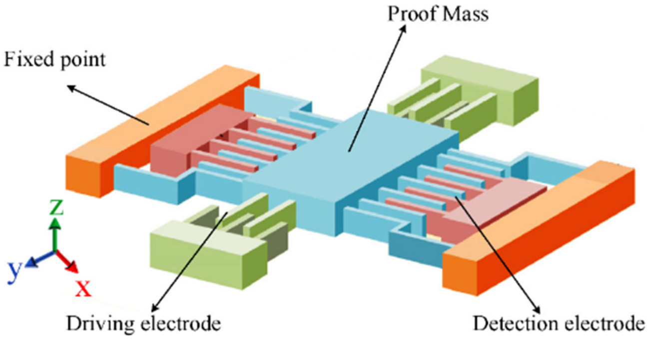

Figure 2 Moving structure of a single axis force feedback MEMS gyroscope [4]

As gyroscopes can measure yaw, pitch and roll, they are key components in any automotive application requiring dynamic sensing, especially when combined with an accelerometer. They are vital for detecting vehicle orientation, which is the pre-requisite for e.g. navigation, dead reckoning, alignment of perception sensors and numerous safety applications e.g. assisting stability control by detecting skidding. They are also the enablers for dynamic headlight adjustment.

4 Overview of headlight systems

Headlight systems can be divided into three different categories. These categories are manual, static and dynamic systems. The following sections will look at these different types in respect to requirements and algorithm complexity.

4.1 Manual headlight alignment systems

In manual systems, the optical axis is adjusted by the driver through an electrical control panel, which controls the actuators in the headlight leveling system. The system does not require algorithms or input from other vehicle systems, which makes it simple and cost effective, but does not comply with the forthcoming UN safety regulations. Further review of manual alignment is out of the scope of this article as this is a yielding application and is unrelated to MEMS sensors.

4.2 Static automatic headlight alignment systems

The static alignment systems are the first step of automatic alignment. The systems can correct the optical axis of the headlights based on shifted vehicle pose from passengers and other loads affecting the vehicle, while it is stationary. Traditionally static systems are based on suspension height sensors. These consist of a reference height sensor and primary measurement sensors, which are located close to the suspension and are connected to each other by wires. An alternative way is to use 3-axis MEMS accelerometer sensors instead. The accelerometer sensor measures how gravity is distributed among the X-, Y- and Z-axis of the sensor and this data can be used to calculate the vehicle tilt.

The basic vehicle tilt calculation using accelerometers is very simple. However, accelerometers are affected identically by road angle, static load and acceleration or deceleration of the vehicle, which means that using only accelerometers, it is extremely difficult to determine if the vehicle is on a flat section of the road or pointing up- or downhill. That is why input from other vehicle systems, like wheel speed sensors, is needed for the system to distinguish when it is allowed to adjust itself based on sensor data [5]. This also contributes significantly to the complexity of the alignment. To optimize the input from several sensor sources, usually the use of a Kalman filter algorithm is required. Kalman filtering solves complex statistical optimization problems in efficient way. F. Gustafsson provides a good general explanation for Kalman filtering [6]. The drawback of Kalman filtering is that is needs a linearization point, in other words, utilization of a very high-performance sensor.

4.3 Dynamic headlight alignment systems

The effectiveness of the static systems has its clear limits, as the road angle and vehicle speed are constantly changing while driving. Without the system’s ability to adjust to e.g. bends, hills and accelerations, light beam heading will differ from optimal and reduce safety by causing glare. It must be noted, that during acceleration or deceleration, the vehicle does not only pitch, but also rotates around the center of gravity. To observe all the relevant dynamics, a six-degree-of freedom inertial unit is required; dynamic alignment systems should be equipped also with a gyroscope able to measure the change in yaw, pitch and roll.

5 MEMS Sensors in head light levelling

As mentioned previously, height sensors have been traditionally used in the static alignment systems, but they have clear disadvantages in comparison to the MEMS sensor-based solutions. MEMS accelerometers use gravity as the reference point and can measure in all three axes, which allows the sensor to be a standalone system and be placed much more freely on the vehicle. Placement can be determined for example to optimize measurement conditions, which is the opposite with height sensors, as the location is tied to be close to the suspension. Since height sensors are connected by wiring, it adds size, which poses even more restrictions for its use as a general solution to cover various vehicle models within the OEM lineup. These are factors that lead to vastly increased cost.

The accuracy requirement for headlight alignment derives from the headlight regulation. Based on what height the headlights are mounted to, the regulation defines a certain percentage-based angle limit, within the headlight alignment must stay from initial downward position under all static conditions. This is shown in Figure 3 [1]

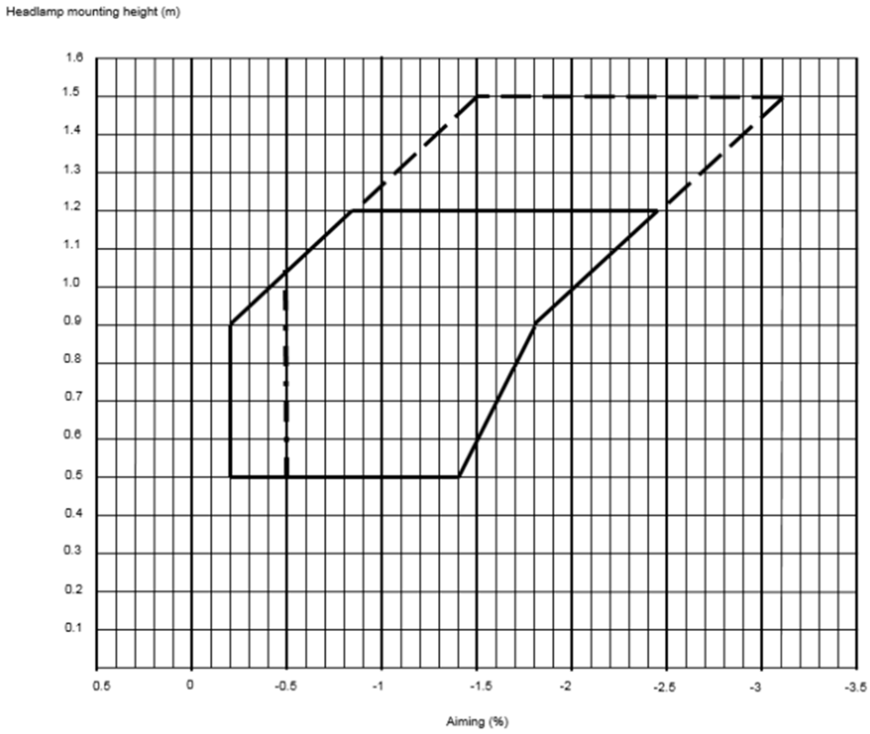

Figure 3 Headlight aiming angle range in percent in comparison to headlamp mounting height [1]

The measurement setting for the percentages is defined in law by the European commission and is derived from Figure 4 [7].

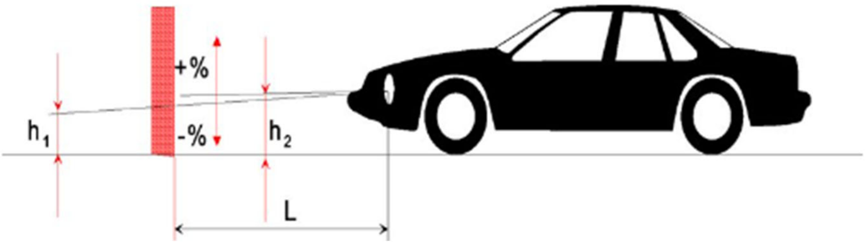

Figure 4 Dipped-beam inclination [7]

If we assume a headlamp height of 0.7m, the above graph shows that aiming angle must stay within -0.2% and -1.6%. This means that aiming accuracy must be 1.4%. In the regulation it has been defined that 1% corresponds to 10mrad. This means that the previously calculated 1.4% sets accuracy requirements of 14mrad, or around 0.8°. If we further assume the very simplified static system below in Figure 5, where the accelerometer sensing axis X is perpendicular to the gravity vector, the gravitational acceleration corresponding tilt angle is given by equation 1

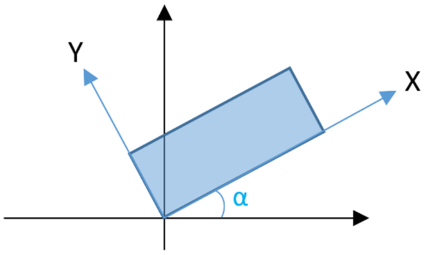

Figure 5 Simple coordinate system for MEMS accelerometer inclination

$$\mathrm{a} = \sin\alpha \times \mathrm{g}, \tag{1}$$

Where a, is the acceleration corresponding to measurement angle α, input in degrees, and g is the gravitational constant in g-unit.

When applying 0.8° to equation 1, we see that the accelerometer must be able to maintain a range corresponding to below 0.014g or 14 milli-g sensor reading. As the reading can shift to both positive and negative direction, this eventually means that the maximum tolerable error is ±7mg. In this small scale, factors like noise and sensitivity play a key role in determining alignment accuracy. These are factors that must be taken into account when using MEMS sensors and they set tight requirement for sensor performance. Further, to ensure compliance to the law, guardband against the requirement must be set and eventually, the accuracy requirements for the MEMS sensor must be defined by the OEM.

The issues mentioned above disturb the measurement already in static conditions, but become immensely more distractive in dynamic conditions. As the vehicle is now moving and the surrounding is changing in a short time scale, factors like temperature stability become important, as sensor output may be affected by ambient temperature changes caused by weather changes or for example driving into a garage. Bad road conditions or gravel chipping induce vibration, which poses a risk of signal saturation if the vibration robustness of the sensor is not on adequate level. Drift over lifetime must be considered as well for the algorithm to maintain consistent and safe headlight alignment throughout vehicle lifetime.

On top of accuracy and robustness, timing becomes very important in dynamic applications. A system that is constantly behind the real-world situation in adjustment, might even perform worse than static headlights. Since the bottleneck of the alignment is usually the mechanical actuators, the electronic control unit sending adjustment commands to them must have the information available with as low delay as possible. Kosman et al. proposes, that a near-satisfactory glare level requires a system latency time of less than 220ms or, 350ms to achieve a barely acceptable glare level [8]. Processing the sensor data through the complex alignment algorithms does require some calculation power, which must be considered in system design.

6 Algorithm

The inputs considered for headlight levelling algorithms in this context typically are inertial sensors and odometer. In addition, GPS, map-database, optical, and acoustic level sensors have been considered by Nilsson [9], who also provides the related mathematical calculations.

The task of filtering algorithm is to extract road grade from gravity and acceleration. Using six-degree-of-freedom sensor set, the equation 2 is extended to accelerometer triad measurement, providing a measurement of specific force:

$$\bar{a}_{SF}^{B} = \frac{d}{dt}\bar{v}^{B} - \bar{g}^{B} + \bar{\varepsilon} \tag{2}$$

The gyroscope triad measurement provides information on body-fixed frame rotation, which refers to the frame where inertial sensors are fixed to. This is done via

$$\frac{d}{dt}\boldsymbol{C}_{B}^{I} = \boldsymbol{C}_{B}^{I}\boldsymbol{\Omega}_{IB}^{B} \tag{3}$$

, where the actual gyro measurements are $\omega_x, \omega_x, \omega_x$ in

$$\boldsymbol{\Omega}_{IB}^{B} = \begin{bmatrix} 0 & -\omega_y + \varepsilon_y & \omega_z + \varepsilon_z \\ \omega_y + \varepsilon_y & 0 & -\omega_x + \varepsilon_z \\ -\omega_z + \varepsilon_z & \omega_x + \varepsilon_x & 0 \end{bmatrix} \tag{4}$$

These fundamental equations contain only reference frames B (body-fixed frame) and I (inertial frame). The link to the present application is via $\bar{g}^{B}$ term and $\frac{d}{dt}\bar{v}^{B}$ term: gravity has known direction in locally level frame and vehicle motion is constrained by the road, giving information on $\frac{d}{dt}\bar{v}^{B}$. Obviously, the noise terms ε masks the relevant signal. An efficient way to estimate such ‘inaccessible’ information buried in stochastic dynamic systems is, as mentioned before, a Kalman filter. It should be noted that inertial sensor filtering techniques are in common use in aerospace applications. New applications to these techniques emerge as MEMS technology develops at fast pace.

The common requirement for accurate estimation algorithms is that the errors in sensor signals must be stochastically predictable. Discontinuous signals may cause filtering algorithm divergence, and this is not permitted when considering the safety aspect of this application.

Accelerometers in headlight levelling systems were considered by Nilsson [8], but the conclusion was that the sensors available at the time of study do not perform on required level as the noise characteristics of the measurement prevented long term estimation of pitch angle. Essentially this means, that the signal was not continuous enough for the filtering algorithm to work as intended. Nowadays there are already MEMS sensors available, that can fulfil the tight accuracy criteria mentioned in the previous chapter and provide sufficiently low-noise and continuous signal to enable functioning filtering algorithms [10].

Commonly known integrity monitoring algorithms should be also involved – modern cars can provide redundant information for this purpose. The same sensors and algorithms can be also used for perception sensor and camera alignment. These applications are becoming critical for the advanced driver assistant systems.

7 Conclusion & Summary

The headlight levelling applications set high performance and robustness requirements for MEMS accelerometer and gyroscope sensors. The dynamic alignment application requires very low noise sensors, which are stable in changing temperature and vibrating environments and keep their capability to provide accurate measurements over the vehicle lifetime. The alignment process involves challenging estimation tasks, and efficient data processing techniques are required to obtain a low latency solution. As the performance requirements are tight from every aspect, this application is a good showcase for modern high-accuracy MEMS technologies and paves the road for also other new automotive applications within the vehicle.

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