Advanced systems for motorcycles based on inertial sensors

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Abstract

Based on an explanation of the MEMS Sensor technology, future system potentials will be explained.

Specific restrictions and advantages of inertial sensors are demonstrated.

Customer expectations for future development targets of motorcycle systems will be discussed.

It is shown which multipurpose use of inertial sensors for safety, performance and comfort systems is possible.

1. Introduction

Within the modern motorcycle technologies sensors for drive train and drive dynamic control systems are a solid contribution to future development. Regulations to minimize emissions and processes to enhance passive and active safety can only be met and achieved if sensors deliver the necessary data. This also applies to all targets in terms of performance, fuel consumption in modern engine designs.

This data acquisition is particularly adapted to the requirements of these systems which control the step in data conversion. The technology which is used has physical limits and limits which are related to situations at the mounting location. To understand the background of those limitations it is necessary to have a basic understanding of the technology which is used.

For vehicle dynamic systems MEMS technology is currently the most complex one, surround sensing by radar, video or ultra sonic is coming next. These ones will make their way into the motorcycle to build up connections with other traffic members and all environmental conditions.

2. MEMS Sensor technology

The Bosch MEMS (micro-electro-mechanical systems) sensors use microscopically small springs, bars, weights, or membranes to make their measurements. The structures etched into their silicon substrate are just thousandths of a millimeter across. Since micromechanical sensors produce only weak electrical signals, experts have integrated electronics either into the component housing beside the sensor or sometimes even directly on the same chip. These take the weak signal and either process it, amplify it, or convert it into digital data. In this way, MEMS sensors can provide measurements directly to control units.

Since the start of production in 1995 MEMS sensor technology is used in the automotive and consumer electronics industries.

2.1 Manufacturing of micromechanical structures

In the past manufacturing of acceleration sensors and gyroscopes was very expensive and mainly used for military purposes. For extended distribution of ESP ® in cars there was a need to find a process with lower costs and made with high volume equipment already available. At the same time it was necessary and mandatory to minimize the size of elements to meet the cost targets.

By using gas vapor etching into depth of a silicon wafer and semiconductor mask processes it is possible to create micromechanical structures which are highly reliable and very robust. There is also no aging measurable.

This procedure is shown in a simplified way in figure 1.

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MEMS technology: surface micromachining

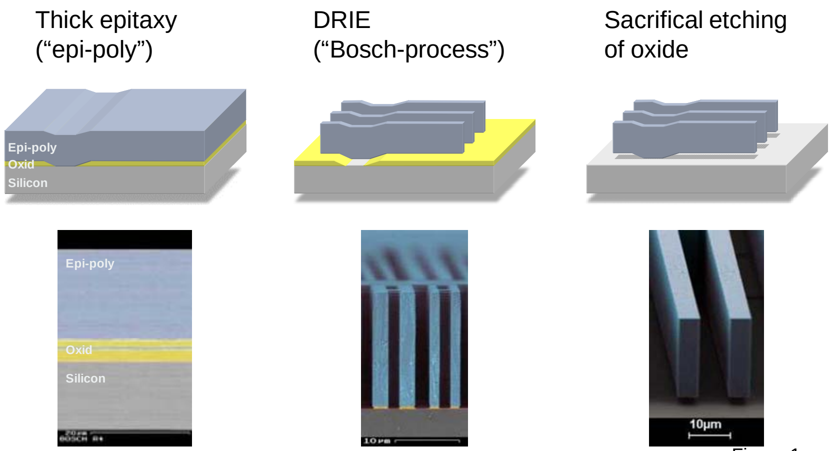

Figure 1

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By using high volume production equipment in semiconductor factories this technology is taking advantage of all kinds of evolutions with increasing wafer sizes and a still ongoing minimization of structures width. A drawback for small volumes is that they have to stick to targets of mainstream designs for car or consumer applications. Currently none of the motorcycle systems is giving enough volume to justify a specific design.

2.2 Packaging technologies

Similar to the manufacturing of measuring devices all volume based criteria are valid for their packaging. In addition to the electrical necessities the mechanical behavior of a package and the internally built up steps have a significant influence on a micromechanical sensor.

This package design has to be measured and validated in combination with functional principle of the sensing element.

Today systems are offered 9 DOF (degree of freedom) for consumer applications. This means 3 axis acceleration, 3 axis rotational acceleration and 3 axis magnetic compass sensing. For safety related applications there is still a more conservative design in use. Single elements are staked up with separate customized evaluation circuits.

How this done is shown in figure 2.

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Packaging of sensor elements

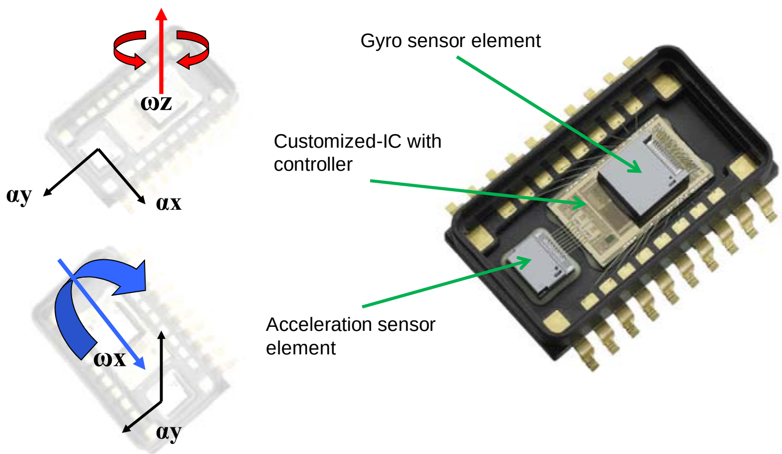

Figure 2

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For safety systems a particular reliability and long term stability of sensors is part of the self monitoring, failure detection and diagnostic capability.

Packages have to be understood as oscillating systems. Therefore an additional development expense has to be spent.

Oscillating modes of a package are shown in figure 3.

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Oscillating modes of sensor package

High movement
Medium high movement
Medium low movement
Small movement

linear movement cross direction | linear movement longitudinal direction | rotation

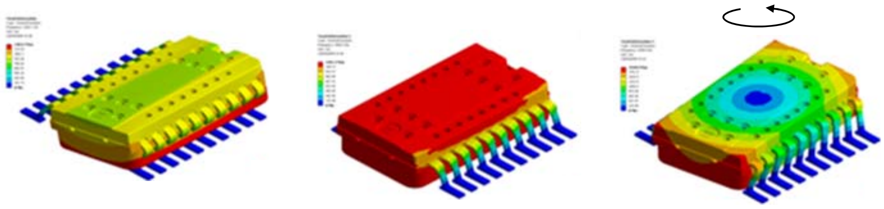


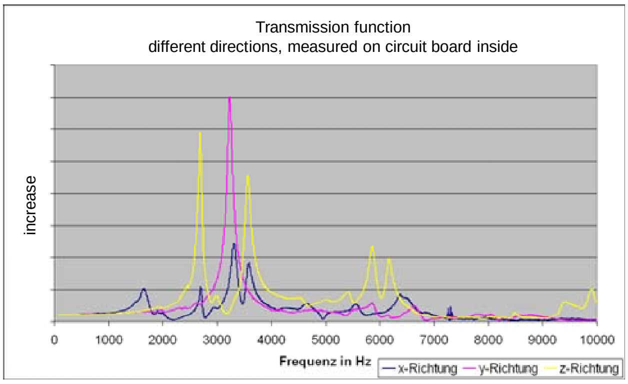
Figure 3

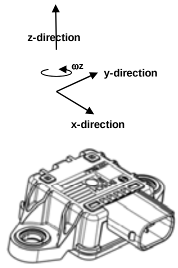
At the end of the manufacturing chain the mounting of sensor devices on a circuit board is part of the total design. Since there are in plane devices available, the cost of unit packaging has dropped significantly. For the assembly process standard soldering equipment is used.

The final sensor package is firmly connected to the vehicle and has to be seen as an oscillating system.

Sensor housing modes are shown in figure 4.

Oscillating modes of sensor unit





Sensor elements:
Yaw rate sensor ωz
Accelaration sensor ax
Accelaration sensor ay

Figure 4

2.3 Testing and release

During manufacturing of measuring devices a specific testing is applied to all devices at various temperatures. This takes place after the packaging process and the final completion of the sensor. In comparison to standard semiconductors these tests have a mechanical segment as well. This makes this testing much more expensive because it is done with specifically designed equipment. To maintain quality and reliability of the entire system testing in production is developed from release procedures during development.

A typical test flow is shown in figure 5.

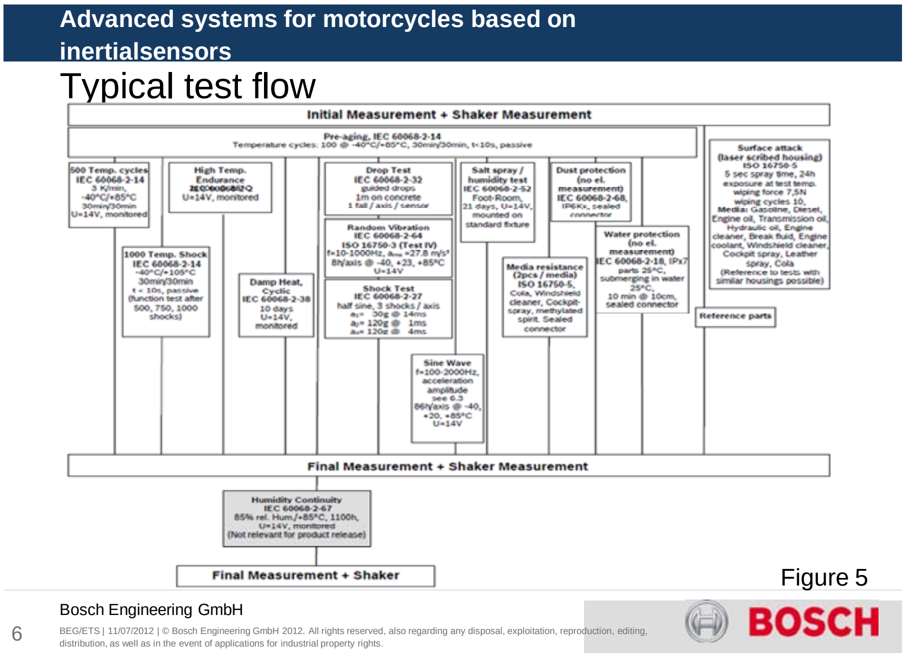


Figure 5

To get a release for a safety system a sensor has to meet all test conditions.

2.4 Application of micromechanical sensors on vehicles

To understand micromechanical technology for motorcycles a basic understanding of the testing and release processes is necessary.
For a functional evaluation knowledge of stress load from existing vehicle applications defines the base line. Beside the classic profiles of temperature and humidity cycles the most important significance for the electromechanical structures is coming from the vibrations of chassis and engine.

With a simple visual assessment of the installation location of the sensor it is not possible to determine which frequencies and amplitudes will appear.

Motorcycles are very specific in this respect due to the fact that in most cases the engine is firmly screwed to the frame and in some designs the engine is part of the main frame. If these combinations also have aging effects, they have to be assessed as well.

How different two sensor units react to distortion from outside is shown in figure 6.

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Comparison of distortion response

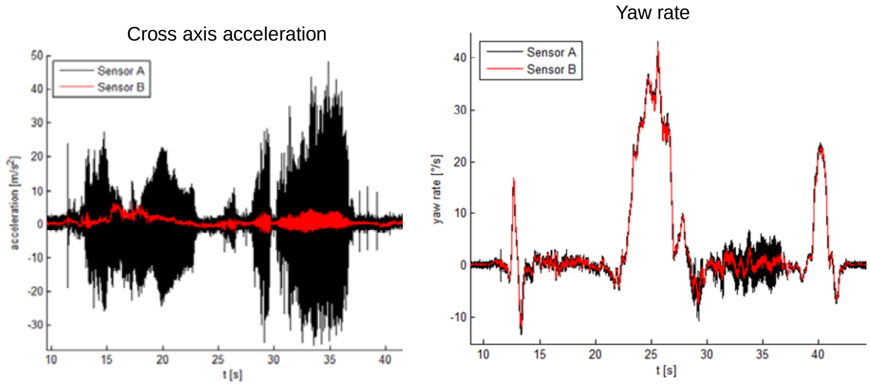

Figure 6

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Currently a sensor technique has to be validated under mentioned conditions in relation to its cross functional interaction. In most cases additional mechanical damping measures are required to achieve the specified functional reliability. This explains why aftermarket solutions have to be seen with somcare.

On the other hand this can lead to the recognition that if modern technology shall take place, it has to be integrated into the entire vehicle design at a very early stage. Sensors used in a motorcycle have to be an integral part of development. Only by doing so savings in terms of time and expenses are achievable.

Nevertheless the exceptional diversity of engine, chassis designs and material variation will not allow plug and play solutions.

2.5 Use of algorithms for not measured vectors

In theory three axis of linear acceleration and three axis of yaw rate are necessary to control the movement of an object in space. Considering present-day costs of measurement elements and associated mounting space in a sensor unit, it makes sense to calculate not measured missing vectors of move out of others. There is enough calculating power in a microcontroller to meet timing and precision demands of systems using this data.

To optimize this calculation it has shown that a specific mounting position has a positive influence.

Standard and 45/90 degree mounting on a bike is shown in figure 7.

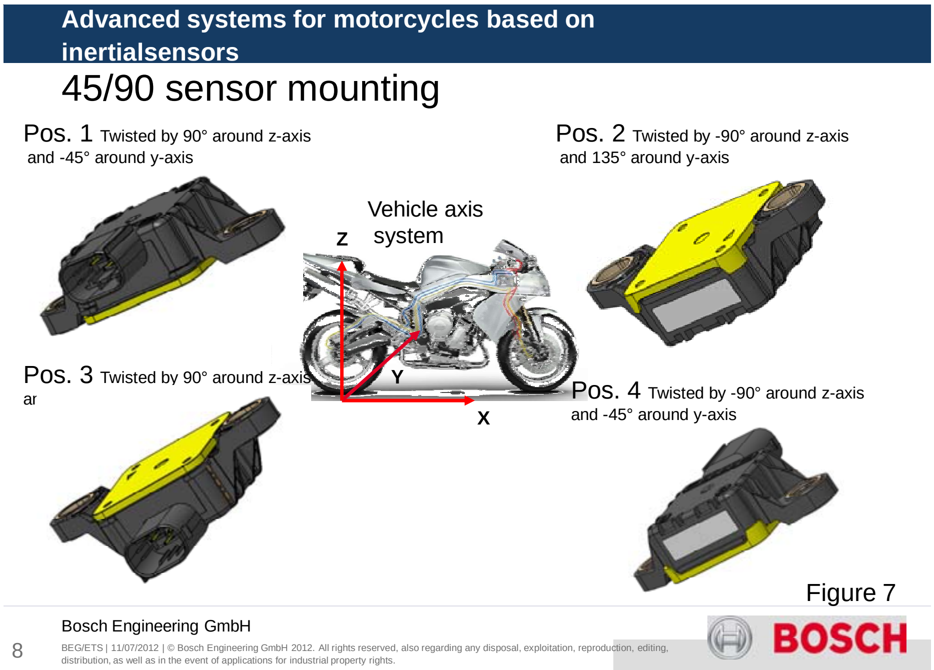

Figure 7

But the calculation effort is not small and also large time differences between the signals which are used for this calculation create large misalignments. Therefore it is an advantage to do the calculation within the sensor itself.

A convertion of raw data of the measure elements into a scalable physical dimension is the start point of a multiple usage in existing or future systems.

This means it is generally possible to transmit raw data into another unit e.g. an engine management unit or an ABS system and do the calculation in those.

However, there are advantages for the embedded algorithms like:

- Timing independent development
- No real time conflicts in signal fusion
- Simplified distribution of physical data to systems of various suppliers
- Only little on-cost but some economy of scale

3. Systems with inertial sensors

Electrical and electronic systems in modern motorcycles can be divided into three main categories:

- Systems for the drive chain
- Vehicle dynamic systems
- Comfort systems

This kind of listing does not mean anything in terms of safety or availability. It is also quite clear that there are flowing borders. Another definition could be done by separating functional blocks like:

- Engine, transmission, actuation
- Brakes, chassis with wheel suspension and tires, steering parts
- Lights in general, operating units, driver information, entertainment

For system functions there are only two factors:

- Regulations by law and standards
- Meeting customer expectations and customer benefits

On the one hand it is sensible to fulfill the regulations and standards to reduce emissions and to increase safety, on the other hand it is most important to meet customer expectations for motorcycles. They are mainly used for leisure time and pure economical aspects are of second order. Therefore it is necessary to focus on these expectations in development. A purchasing decision will not be made by the size of a microcontroller in engine management or memory space of an ABS. The outcome of system features attract customers and drive new designs.

For sensors a statement is valid which says: What could a sensor detect better, faster, independently, more objective than a human being? Sensors have to deliver this information, a system has to react as expected. But it in some cases it is also true that only since a sensor and system has been introduced, customers demand this particular functionality.

The value contribution to the motorcycle is defined by the user.

3.1 Traction control

The control of the drive torque at the rear wheel of a motorcycle is already shown in various system layouts. In comparison to a car there are two major differences. First, the motorcycle can lift up its front or non-driven wheel and second, it can lean into corners.

Out of a µ-slip curve it is possible to see the basic problem of traction control during cornering.

A typical µ -slip curve is shown in figure 8.

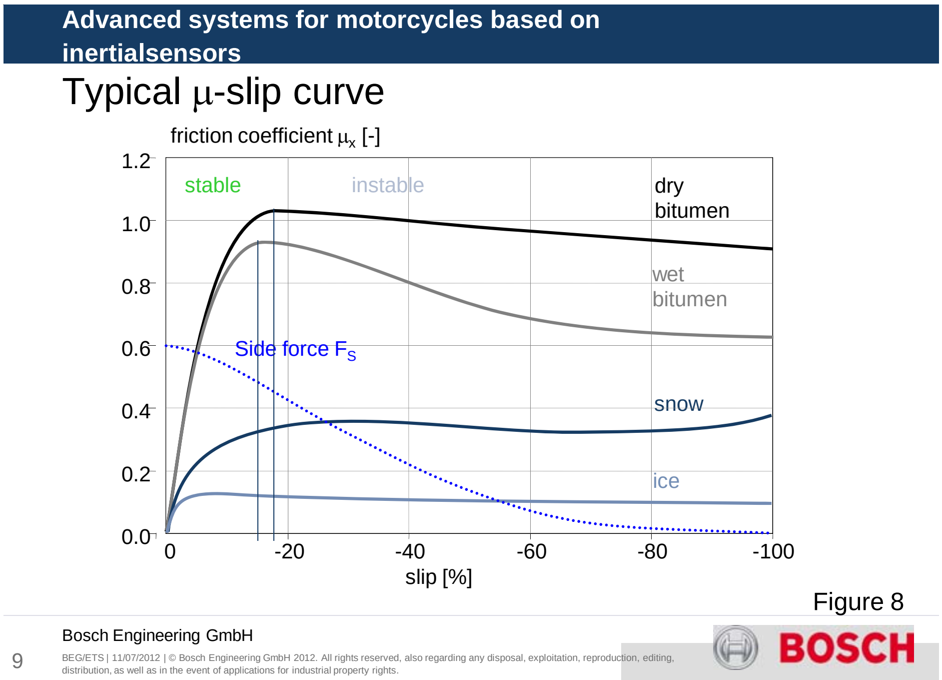

Figure 8

This curve has variables, e.g.

- Tire temperature
- Tire type and shape
- Road surface structure
- Tire pressure

The maximum of the friction coefficient is typical at 10% to 18% slip. That means

V wheel = 1,15 x v vehicle

This value is a little bit higher than in case of a braking situation because of grip into road surface and tire deformation.

If a slip control is only done by comparison of front and wheel speed, it has some significant limits.

Due to the fact that the shape difference between front and rear tire of a motorcycle already creates a speed difference in the vicinity of the maximum in the µ-slip curve. It is easy to understand that compensation is necessary.

Lean angle versus wheel speed difference is shown in figure 9.

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Lean angle versus wheel speed difference

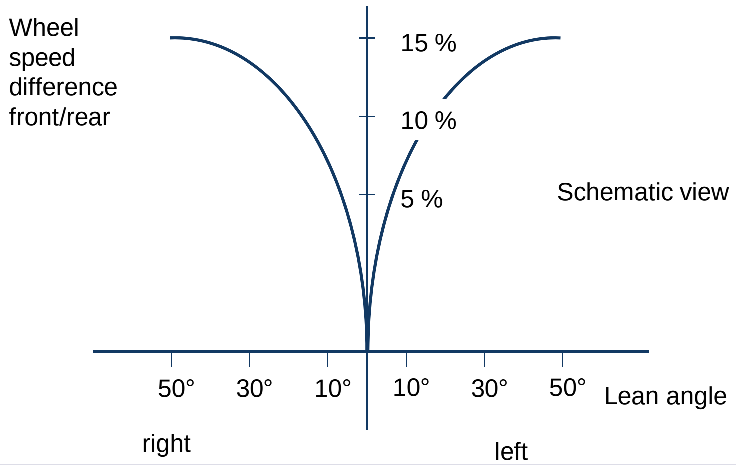

Figure 9

It shows that at higher lean angles a part or even the total speed difference is used by this geometrical base line. But the limit of side force and drive force is still not given as known from “Kamm’schen Kreis”. For that reason it is of advantage to implement the lean angle into traction control strategy to meet maximum performance and safety requirements during cornering.

Today’s lean angle sensors deliver not only a lean angle information. They provide information on longitudinal acceleration and vertical acceleration. This has a big advantage for a traction control system especially if the front wheel is lifted up. In this case a synthetic vehicle speed can be calculated and can be engaged into the control algorithm.

Today lean angle sensors can only calculate the angle of between the axis of gravity and the vehicle center line. There is no information about the angle of the road versus the horizontal line. On public roads this angle in combination with the corner radius can be neglected. For racing this could be of importance to find the limits.

Tolerances of the calculated lean angle in relation to a high precision measuring tool are shown in table.

Measuring range	+/- 180°
Angle failure relative	+/- 1,5°
Offset	compensated
Start up time	< 500ms
Phase shift to reference	< 10ms

Because the driver is a moving part on the total bike system, the axis of combined axis of gravity is not the same as the center line of the bike.

Scheme is shown in figure 10.

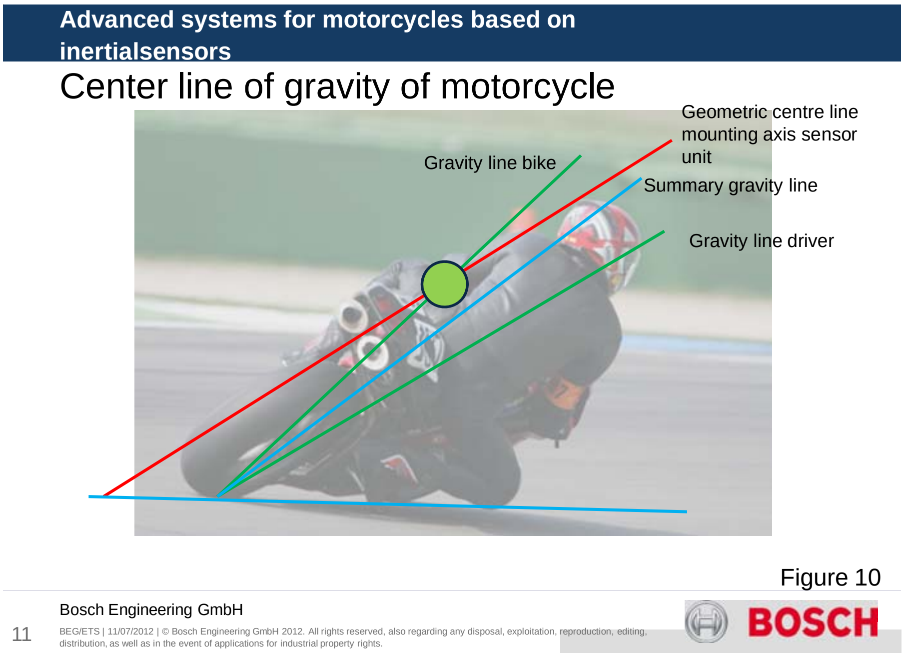

Figure 10

This simplified view already shows that it is not possible to calculate the lean angle with acceleration sensors. For an optimized traction control with the best compromise between performance and stability it also requires gyroscopic information of at least two axes.

How this information is used in traction control algorithms is the core knowledge of system suppliers and vehicle manufactures. The engine character is another significant parameter of these algorithms.

3.2 Wheelie control, launch control

A lift up of the front wheel is a very common reaction of powerful motorcycles and even worse in combination with a short wheel base and a high center of gravity. For drivers with less experience it is scaring, for others it part of the vehicle dynamic to get the maximum acceleration. In some cases it is said to be a fun feature.

The system detects the rising front wheel but the simple reduction of the drive torque could be unpleasant for the driver. The realization of this control in a most harmonic way is a development target for the next generations of bikes. To control the turning impulse to get a defined distance of the front wheel to the road surface would meet customer expectations. In order to get this done it is necessary to know the slope of road as well.

It is possible to detect the rotational acceleration along the y-axis with a sensor element orientated accordingly. In the sensor unit MM5.10 this value is calculated from signals of other elements than a specific y-yaw element. It is beneficial to have a mounting in the 45/90 degree orientation to get a fast output.

To include the slope of the road into control algorithm the sensor sends out this information in relation to the horizontal line. Because loading of a bike and driver movement is a variable parameter, a real wheelie control needs a sensor unit.

A special format of a wheelie control is named launch control. The lift up of the front wheel is a drawback for this function too. For the calculation of the vehicle speed, there is only one information coming from the rear wheel. A synthetic vehicle speed can be derived from the acceleration value measured by a sensor.

To achieve an optimum of acceleration it is necessary to know the value of friction coefficient. This value cannot be measured directly, it has to be assumed on the basis of other information. One possibility is to use the shape of μ-slip curve at its maximum.

Motorcycles do not have a stable driving condition. Therefore sufficient safety margin has to be taken into consideration for these functions. Customer expectation and abilities to react should not be stretched too far.

3.3 Crash detection

For a crash detection there are some different ways to come closer to this subject

- Crash avoidance
- Reduction of severity
- False free detection
- Estimation of severity of damages

In addition to the drive dynamic parameters like speed, angle, and acceleration of the vehicle there is more information required, e.g. the time interval of parameters before and after instability, the effect of obstacles, deviation of bike and driver and co-driver, road path and location by GPS.

Crash detection is still at an early stage of research and in particular there are very rare data sets for evaluation of movements available. The interaction of driver and motorcycle is not sufficiently supported by measured data.

It is known that a reaction of a human is different in predicted or in unpredicted situations and causes different behavior standards. The driver’s reaction is significantly changed by training effects as you can see in every motorcycle race.

For this paper we will concentrate on the drive dynamic of the vehicle.

Instability conditions of a motorcycle are shown in figure 11.

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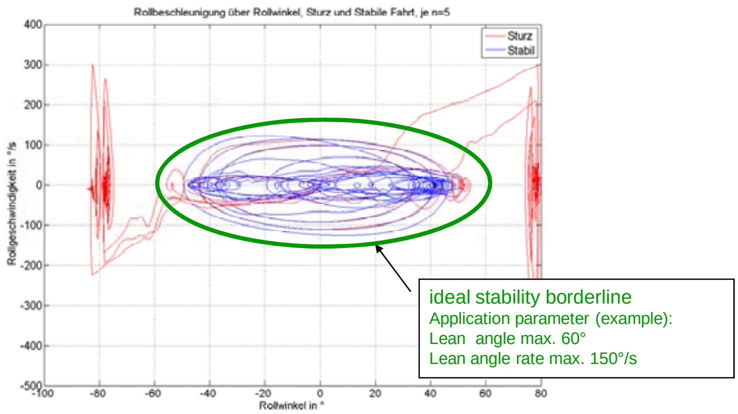
Instability conditions of a motorcycle



- Condition space view for lean angle and lean angle rate
- Stable condition inside of a stability borderline (green circle)
- Detection of instability when borderline is crossed

Figure 11

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The data assessment clearly shows safe and unsafe zones. It is not too daring to say that a final instability starts long before the driver can perceive it. It seems to be possible to determine the final Low-sider or High-sider at an early stage if there is no adequate counter action.

There is a huge chance for research in this field to assess these data sets in a way to initiate appropriate counter actions like using the brake or reducing drive torque but both could be wrong. A Low-sider does less harm to the driver in some situations than a High-sider.

As a basis for a calculation you also need beside multi-axis data from measuring devices recordings of data over a mandatory period of time. The necessary computing power, memory space, and special algorithms to select filters for this task are not realized in today’s sensor units. It is not completely clear how big the total effort would be.

Additional action has to be taken to understand the location of the driver. Is the person still on the motorcycle? By plausibility checks and for example using a sensing device on the seat or handle bar it might be possible to gain a better insight.

3.4 e-call

A reliable crash detection is needed in order to realize an e-call function. But on top other information and information channels have to be built in.

Such a system has to be a part of the entire motorcycle electronic architecture. Getting excess to a communication network, realizing an emergency power supply are independent tasks for design and development.

In terms of crash detection there is a need to categorize a crash situation and its history into certain classes. With such classes an emergency center can start adequate actions. These classes have to be nationally and internationally the same.

For a system development it means that the assessment criteria have to be public and common sense.

3.5 Semi active suspension

Spring and damping set up of the suspension system is a major contribution to driving stability and driving safety more than in any other vehicle.

Customer expectations highly focus on the function of the suspension system but are also to some degree very diffuse. For engine power or stopping distance a measurement in physical dimensions is an objective matter. For suspension systems on chassis many individual preferences with a wide spread of experience is in place. Therefore a standard set up is a compromise given by the manufacturer.

A lot of people don't know about the effect of manual changes on spring rate, spring load and damping parameters. A system which takes over the task of variation of suspension adaptation to driving conditions can increase drive safety and trust into the performance of the complete chassis.

With the introduction of central sensor unit it opens up the door for the use in a semi active suspension control.

In volume production it is not economical and in terms of robustness useful to take long distance travel sensors to measure the dynamic values of the unsprung mass.

One of the alternatives is to use an acceleration sensor to measure the wheel movement. There is a good chance to integrate such inertial sensing elements into the wheel speed sensor. It allows to see not only vertical acceleration but also horizontal vibrations.

A system proposal is shown in figure 12.

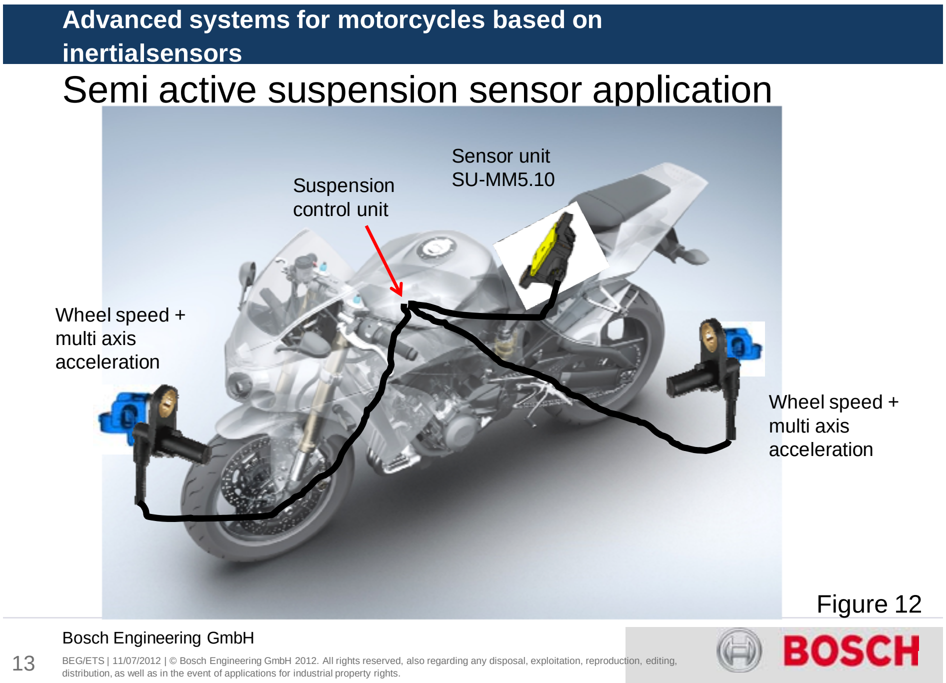

Figure 12

It might become reliable information for brake control systems on rough surfaces and any other instabilities of the front wheel like low or high speed shimmy.

The missing value of static load and its distribution can be calculated from the parameter longitudinal and vertical acceleration and pitch yaw rate if the spring force rate is known.

A cross functional effect of suspension control, drive and brake control is already established in premium cars. It is represents a further step to meet customer expectations. This will come for motorcycles in the near future. The big advantage is the multipurpose use of a central inertial sensor unit.

3.6 Cornering head light

In comparison to cars head lights for motorcycles have not developed that much within the last few years. Nevertheless the first step into this direction came with the cornering light of the GT1600 of BMW.

This innovation was possible because the vehicle already had a lean angle sensor for traction control. This head light system is a sophisticated design part of the entire vehicle and has to fulfill safety aspects which should not be underestimated.

With the latest development of sensor units a pitch yaw rate is available and offers new options.

By compensating the pitch movement of the chassis in a head light control mechanism lighting distance can be adapted. The driving comfort in the dark could be considerably improved by avoiding blinding opposite traffic and having a longer illuminated range during braking.

Schematic view of the pitch control head lights on motorcycles is shown in

figure 13.

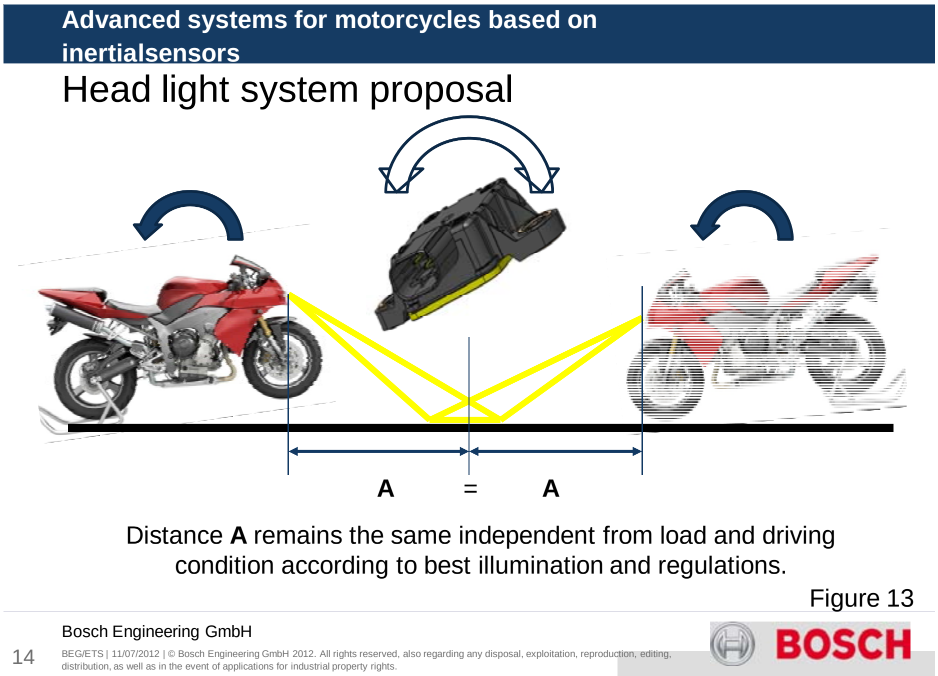

Figure 13

3.7 Cornering – ABS

An ABS-system is with no doubt a very important step to more safety on motorcycles. This importance is underlined by the market reaction and general regulations in the near future.

Based on already many years of development, today modern ABS is on a high level of performance at straight braking. Many variations and conditions of road surfaces are covered with good applications. It is also possible to get system support during braking in corners. Achievable lean angles astonish every person doing such a test.

From drive tests and theoretical assessments we know that there is a strong interaction between the driver and his vehicle, visible during controlled braking in corners. This driver reaction depends on training experience and again on the fact whether it is a predicted or unpredicted situation.

How much the introduction of a lean angle information could improve the handling performance is the corner stone of current research and development projects.

The brake force distribution of systems with electronically management can be improved to a new dimension with the additional information on the declination of the road.

The small size of a sensor unit makes packaging much easier for all kind of two wheelers.

Dimensions and function support of sensor unit MM5.10 are shown in figure 14.

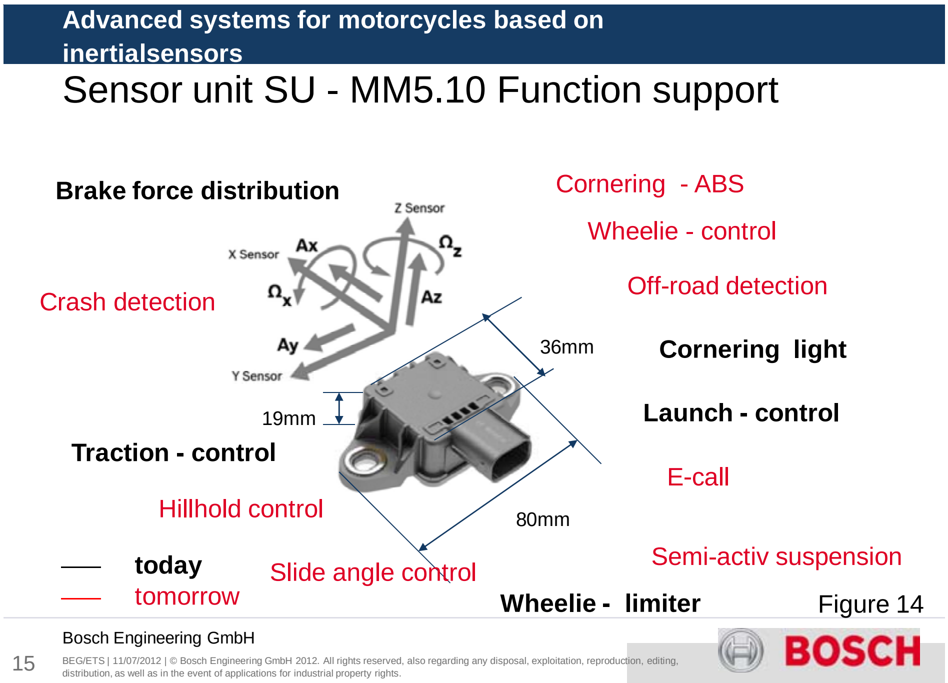

Figure 14

4. Summary

Each of the shown applications of a sensor unit has in itself a high scientific and engineering content and represents the challenge to solve very specific problems in the future.

For the development of technology in modern motorcycles sensors are of high importance to get the best possible drive dynamic performance.

Beside the importance of each single function there is a big potential in combining systems by using information from common sensors.

A closer look highlights the chances for future developments of two wheelers with respect to the driver expectation.

Between technically possible and economically useful solutions a compromise has to be taken.

The use of sensor signals to improve safety, comfort and performance cannot be turned back anymore.

Road safety in future will be secured by sensor based systems.

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