

Motion Tracking in Crash Test Applications with Inertial Measurement Units

Kai Schoenebeck and Joachim Melbert
Ruhr-Universitaet Bochum

Florian Weiser
Volkswagen AG

Copyright © 2009 SAE International

ABSTRACT

A new measurement system for dummy movement and chassis deformation in crash tests overcomes the restriction of blind areas in the existing photo camera observation. An inertial platform technique with micromechanical acceleration and rotation speed sensors is applied. Reconstruction of the original movement with tolerances of a few millimeters can be achieved. Various tests in automotive applications have demonstrated the performance and robustness of the system.

INTRODUCTION

Increasing requirements in vehicle safety demand a careful adjustment of the different components such as airbags and belt tightening systems. Observation of the crash test with high-speed cameras has been established for years. However, in some phases the visibility of certain chassis objects and of crash test dummies is limited. The dummy head for example, is covered by the inflating airbag for some time (Figure 1). Hence, exact motion analysis is not possible during this most critical phase and sufficient information about the penetration depth of the dummy head into the airbag is missing. The remaining safety distance between the dummy head and potential collision objects of the chassis or the steering column under worst case conditions is not generally known precisely enough up to now.

Various principles can be used to bridge this gap. Ultrasonic, static or dynamic electric or magnetic fields,

microwaves or even X-rays have been investigated. Finally, considering the boundary conditions, e.g. performance, robustness and costs, inertial navigation was identified as the most promising approach.



Figure 1: Limited optical observation during a crash test complicates motion analysis of the dummy head

Although inertial measurement is principally well suited for crash test applications, there are major restrictions to be overcome. Limitations due to the availability of space in the dummy head avoid application of high performance sensor systems, such as ring laser gyroscopes. With respect to the requirements of inertial application, existing in-dummy accelerometers for biometrical analysis suffer from a large measurement range of up to 2000 g and extreme bias instability. Advances in Micro-Electro-Mechanical Systems (MEMS) provide an excellent opportunity. Small-sized chip-based inertial sensors are already used in automotive applications, for example airbags and drive stability systems. Angular velocity and acceleration sensors with integrated signal conditioning circuits are available at low costs. MEMS sensors also show limiting factors

such as offset, gain errors as well as noise, which affect the accuracy in navigation applications [1, 2]. However, the long term stability of their parameters offers the opportunity for dedicated calibration and error correction procedures.

A test bench for the inertial measurement unit (IMU) was realized to generate three-dimensional movements with superimposed rotations, similar to real dummy head movements in crash tests. Equipped with high performance instrumentation for position and angle, the curvature versus time is known within tight tolerances. This system acts as a reference for the calculated track, separately computed from the IMU measuring data. The IMU must be precisely calibrated with static and dynamic procedures, and an error correction algorithm is applied. By this, tolerances of less than 5 mm are yielded for the position error on the test bench and for several crash tests in real cars.

MOTION TRACKING

Inertial navigation systems are widely used in many different types of vehicles, including aircraft, submarines, spacecraft, and guided missiles [3]. An IMU consists of three accelerometers and three gyro sensors mounted on an orthogonal triad. Its initial conditions for position, velocity and orientation must be derived from another source, i.e. photogrammetric methods in a crash. The IMU then independently computes its own velocity and position from its own sensor data. All inertial measurement units suffer from integration drift: Even small errors in measurement of acceleration and angular velocity are integrated into increasing errors in velocity, which are even transferred into progressively rising errors in position.

Motion tracking of the dummy head in a crash test is performed over a relatively short period of time of about 200 ms. Therefore the inertial navigation algorithm in Figure 2 can be simplified by neglecting the earth's rotation rate. The IMU presented in this paper, is realized as a strapdown system [3, 4]. The sensor is mounted in the dummy head, the acceleration $\mathbf{a}$, angular rates $\boldsymbol{\omega}$ and temperature ϑ of which are measured internally.

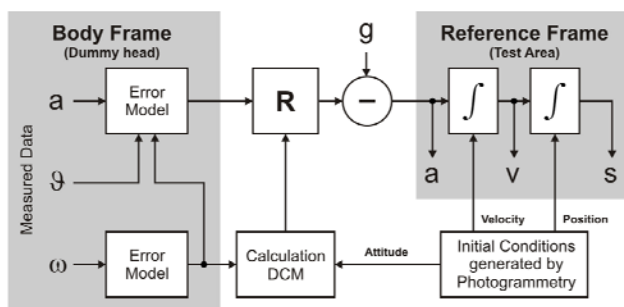


Figure 2: Simplified inertial navigation algorithm [4, 5, 6]

The raw sensor data are preprocessed by means of a sensor error correction model. Then, the calculation of the head trajectory is done in two steps. First, the body sensed angular rates are integrated to compute the matrix $\mathbf{R}$ from transformation of body frame to reference frame. This transformation is performed by the direction cosine matrix (DCM) applying a quaternion approach. In the second step, the transformation matrix is used to rotate the measured acceleration from body frame to reference frame. The output of an accelerometer represents the sum of actual head acceleration and earth gravity $\mathbf{g}$. The sensed data must therefore be compensated for gravity in order to determine the total acceleration of the head. This acceleration can then be integrated once to obtain head velocity and twice to obtain the head position. The initial state of the head (position, velocity and attitude) is provided by photogrammetric methods.

INERTIAL MEASUREMENT UNIT

Dummy head accelerations in crash tests under normal conditions range from 30 g up to 60 g, and depending on the test scenario angular rates can reach up to 1600 °/s. Moreover, it is necessary to guarantee shock survivability, because accelerations at worst cases can overrun several hundred g. Only limited space is available within the dummy head, thus demanding for small-sized IMUs with a volume of less than 50 cm³.

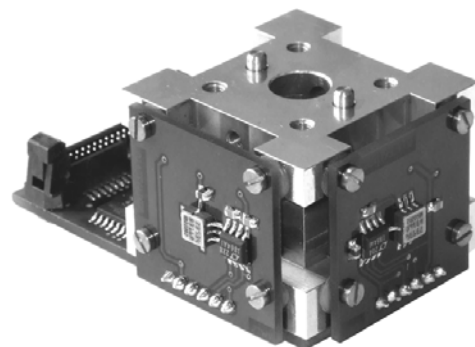


Figure 3: Inertial sensor unit for the dummy head with a measurement range of 120 g and 1800 °/s, signal conditioning and digital outputs

High performance inertial sensor technologies such as fiber optic gyroscopes or servo-loop accelerometers suffer from their measurement range, size, costs etc. State of the art Micro-Electro-Mechanical Systems (MEMS) are integrated into single chips, for either measuring acceleration or angular velocity. MEMS-based accelerometers are already part of standard measurement instrumentation used as in-dummy transducers. These sensors are well suited for biometric analyses but basically not for motion tracking. Therefore, a new motion sensor was developed. It contains a cluster consisting of a temperature sensor, three accelerometers and three gyroscopes with a measurement range of 120 g and 1800 °. All sensor

outputs are sampled by 16bit analog-to-digital converters. Figure 3 shows a respective sensor unit.

Furthermore, a data acquisition system for the sensor signals was designed, as shown in Figure 4. Robust construction allows an application within the car to be crashed. Programmable sampling rates of up to 50 kHz are possible with an acquisition time of several seconds. The system can be triggered via wireless interface or line. Independent operation is ensured by a Li-Ion battery in the recorder. Sampled data will be transferred to a PC via USB after the crash test for offline motion analysis.

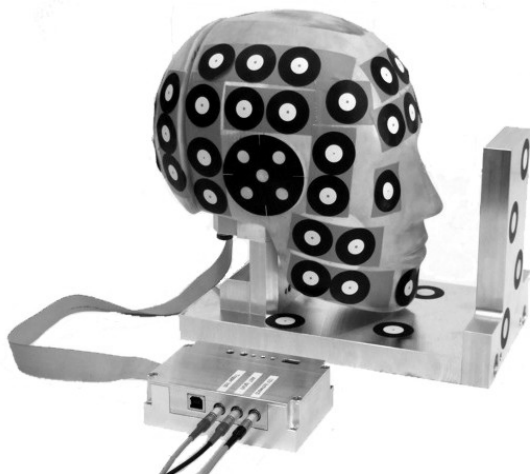


Figure 4: Dummy head equipped with inertial sensor and data recorder

CALIBRATION AND TEST EQUIPMENT

Small errors in the measurement of acceleration and angular velocity can cause large errors in position which is mainly due to the double integration. Although the integration only lasts for a short period of time, a dedicated calibration strategy becomes essential. For example, an offset error of only 0.05 g for a single accelerometer causes an unacceptable position error of 10 mm after 200 ms.

SENSOR ERROR MODEL – The sensor error model for accelerometers and gyroscopes consists of their individual electrical properties and their geometrical tolerances resulting from imperfect assembly inside the integrated circuit, on the printed circuit board and in the sensor package. The following error types are taken into account [6]:

- Offset
- Sensitivity (sensing axis)
- Cross-axis sensitivity / misalignment
- Nonlinearity
- Bandwidth
- Noise
- Temperature drift for bias and sensitivity

The contribution of each individual effect was analyzed in detail. Both, the accelerometer and the gyro cluster model fit into the model described by Figure 5. The most important parameters, sensitivity and bias, are separated into a static part, a temperature varying part and a random drift part. Furthermore, the compensation of accelerations, resulting from eccentric mounting of the sensors, is necessary and depends on the construction of the IMU.

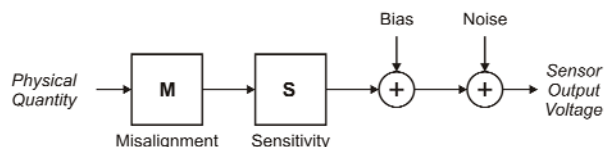


Figure 5: Basic sensor model for accelerometers and gyroscopes

CALIBRATION – Various calibration techniques for IMUs, that are well suited for vehicle navigation, have been published [2, 4, 6, 7]. For the differing requirements of this application, a modified calibration technique was developed.

Accelerometers can be calibrated by using earth gravity **g** as a reference. All vectors in a three-dimensional space can be expressed as a linear combination of three orthonormal vectors. The components of the sensor axis x, y, z can therefore be written as:

$$g_x^2 + g_y^2 + g_z^2 = |g|^2$$

In practice, the sensor triad cannot directly serve for this purpose, due to the non-orthogonality of the real sensor axis. Hence, a transformation matrix **M** is needed in order to correct the misalignment. Taking offset and sensitivity into account, a complete system of equations can be set up for the parameters to be calculated. Evaluation is accomplished by a least square fit based on the interior-reflective Newton method. The whole calibration process comprises at least 24 measurements with the IMU, arranged in different attitudes. An even larger count of different positions was applied for smaller statistical errors.

Calibration device for multi-position calibration

A new automatic calibration unit for multi-position calibration was designed, which is shown in Figure 6. It offers two degrees of freedom by use of two axes of rotation driven by micro stepping motors. High resolution incremental encoders are applied, together with low g acceleration sensors for precise orientation towards earth gravity. The IMU to be calibrated can be positioned in a number of exactly known attitudes. The entire calibration procedure is automated, including temperature control and initial platform leveling. The calibration device is controlled by software running on a PC, where sensor parameters are computed as well.