»GREEN ICT @ FMD« – COMPETENCE CENTER FOR ECOLOGICALLY SUSTAINABLE ICT

Energy consumption of inertial sensors under typical real-world operating conditions, using the example of the in-house ENAS-IMU

A Whitepaper by "HUB 1 –Sensor-Edge-Cloud"

Sven Voigt (Fraunhofer ENAS), Daniel Bülz (Fraunhofer ENAS)

The work presented is part of the »Green ICT @ FMD« project, your competence center for ecologically sustainable information and communication technology. The project is established by the Research Fab Microelectronics Germany and funded by the German Federal Ministry of Education and Research.

Kompetenzzentrum »Green ICT @ FMD«

c/o Forschungsfabrik Mikroelektronik Deutschland FMD
Anna-Louisa-Karsch-Str. 2
10178 Berlin, Germany

Main contact
Sven Voigt
sven.voigt@enas.fraunhofer.de

www.greenict.de
www.forschungsfabrik-mikroelektronik.de

Date of publication
Januar 2025

1. Introduction

In recent years, there has been a sharp increase in the use of miniaturised inertial sensors based on MEMS technologies for measuring acceleration, rotation rate and other parameters. Applications range from wearables and smartphones to robotics and drone systems to industrial monitoring solutions. Parallel to this development, there is a growing demand for energy-efficient sensor systems, as battery life is often the limiting factor for mobile or autonomous devices.

This white paper examines the energy consumption of inertial sensors using the example of our in-house IMU under typical real-world operating conditions. In particular, it looks at how different rotation rates and sampling rates affect power consumption and whether mechanical effects have an influence on the energy behaviour of the system. Finally, practical optimisation recommendations for integration into energy-limited systems are derived.

2. Structure and operating principle of inertial sensors

MEMS inertial sensors (micro-electro-mechanical systems) are miniaturised sensors that can measure acceleration, rotational speed, vibration and inclination. They consist of micromechanical structures integrated onto a silicon chip. The design usually includes a moving mass suspended by fine spring structures. This mass shifts minimally during acceleration or rotation. This movement is usually detected capacitively, less commonly piezoresistively or optically. The resulting change in capacitance is converted into electrical signals that are proportional to the force acting on the mass. Integrated evaluation electronics amplify, filter and digitise these signals. MEMS accelerometers measure inertial forces in one or more directions, while MEMS gyroscopes use the Coriolis force to detect rotational speeds. Combining both sensor types in one system creates a so-called inertial measurement unit (IMU), which provides complete motion and position information in three dimensions. Such IMUs can be found in numerous applications, from smartphones and drones to vehicles and industrial navigation systems.

At ENAS, an IMU was assembled from three self-developed two-axis MEMS acceleration sensors and three single-axis MEMS gyroscopes. The focus of the individually developed sensors, particularly in the case of gyroscopes, is on accuracy and bias stability rather than primarily on energy efficiency. However, compared to optical gyroscopes with higher accuracy, MEMS sensors offer the inherent advantage of compact size and lower energy consumption. A central microprocessor installed in the IMU is used for data collection and sensor configuration, which transmits the data to the measurement data acquisition and evaluation system via a digital interface.

3. Measurement setup, procedure and data acquisition

The measurement setup consisted of a modular test platform that allowed both precise current measurements and flexible scenario control.

The components used were:

- Inertial measurement station consisting of AC1120S rotary table from Acutronic and temperature chamber from Vötch

Fig. 3.1: Inertial measurement station consisting of AC1120S rotary table from Acutronic, temperature chamber from Vötch and control computer

- Sensor module: ENAS-IMU, consisting of three single-axis MEMS gyroscopes and three dual-axis MEMS accelerometers

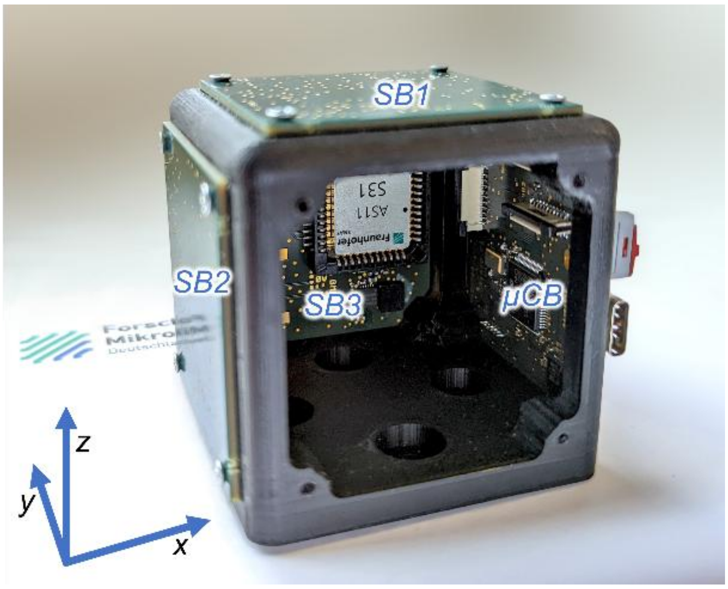
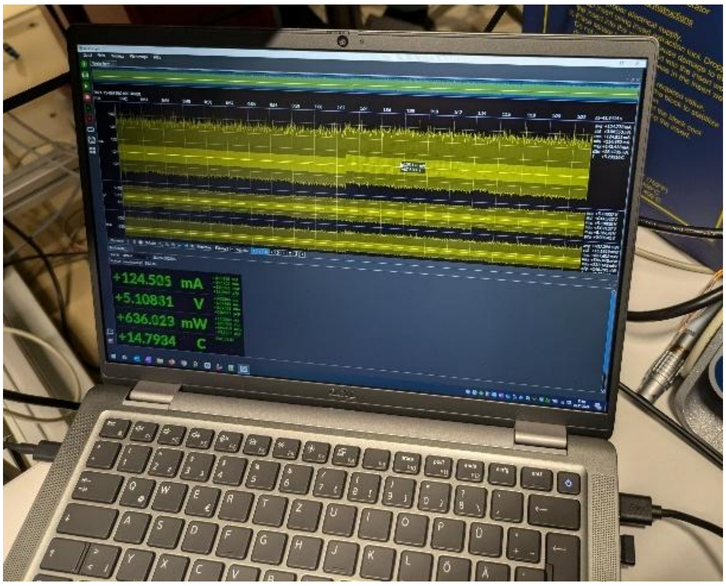


Fig. 3.2: ENAS-IMU with individual MEMS sensors (3x1-axis MEMS gyroscope, 3x2-axis MEMS accelerometer)

- Current measuring instrument: Joulescope JS220

Fig. 3.3: Joulescope JS220 for recording the supply voltage and current consumption

- Communication: UART/USB via sliding contacts on the turntable to the measuring laptop



Fib. 3.4: Measuring laptop for visualising and storing current/voltage/power data from the Joulescope

The measurements were performed at an ambient temperature of 23 °C in a 1g Earth gravity field. The IMU was mounted on a precision-controlled turntable that rotated the sensor unit around the z-axis. Six different rotation speeds were set: 0 °/s, 1 °/s, 10 °/s, 100 °/s, 500 °/s and 1000 °/s. In addition, the IMU was operated at two different output data rates. Specifically, the rates varied between 50 samples per second and 500 samples per second.

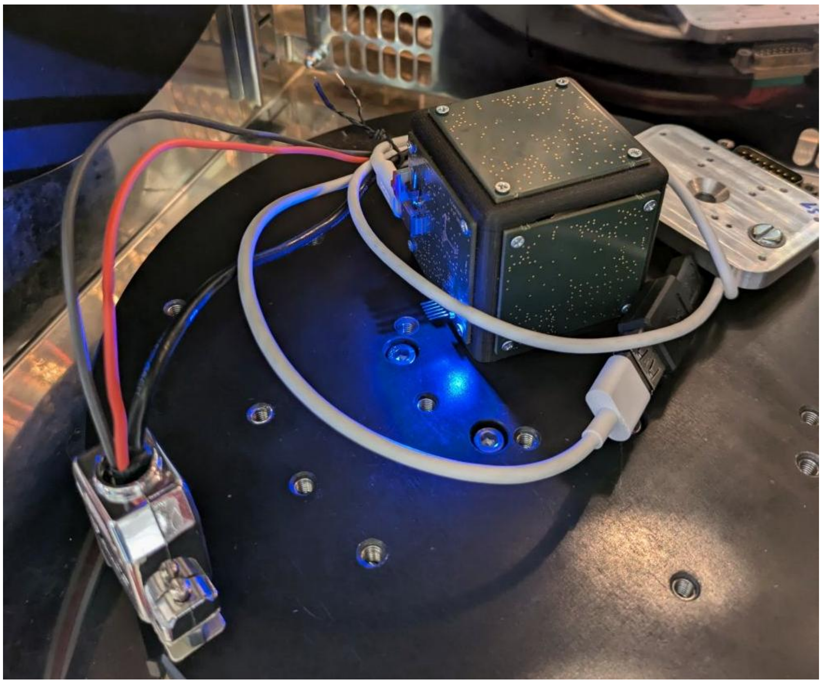


Fig. 3.5: ENAS-IMU on turntable in climate chamber. Connection and power supply via USB

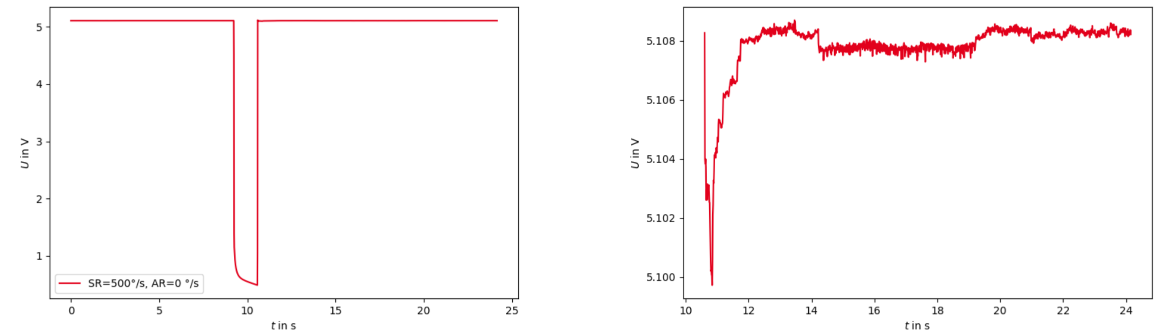
The JouleScope measuring device was used to simultaneously record current, voltage and power. To enable precise measurement of the supply voltage, a standard USB cable (type A to type C) was modified. The supply lines were separated so that both the voltage drop and the current flow could be measured between the 5 V line and ground.

The IMU was powered via the USB port of a laptop and also used for data transfer. Each measurement began with the start of JouleScope recording. The IMU was then briefly disconnected from the system and reconnected to perform a defined system reset. Immediately after reconnection, a five-second measurement began at the configured sample rate.

4. Results and analysis under typical real-world conditions

4.1. Voltage and current curve

The time curve of the measured supply voltage clearly shows the characteristic behaviour during the connection and disconnection of the IMU, which was carried out as part of the system reset. The moment of switch-on can be used as a synchronisation mark between the current measurement and the actual data acquisition.

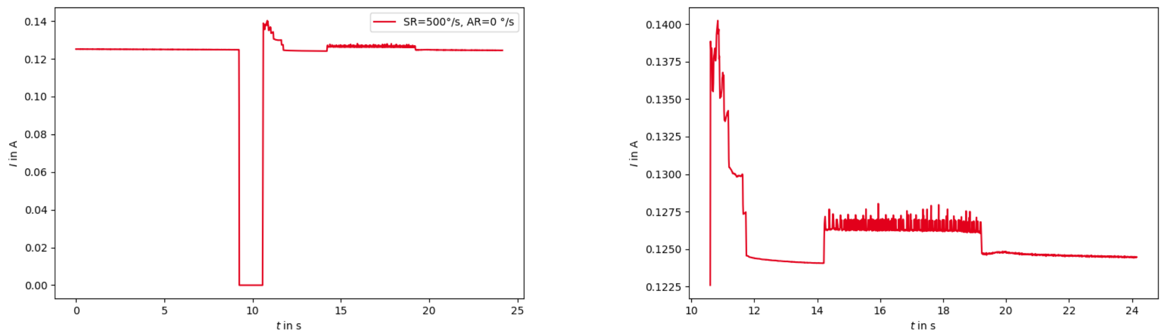


a) *Voltage curve during a measurement – clearly visible is the connection and disconnection of the IMU for the system reset*

b) *Voltage curve after switching on*

Fig. 4.1: Example voltage curve of a measurement

The current curve shows similar behaviour. After switching on, the IMU reaches its stable operating state within a few milliseconds. The recorded current and voltage curves confirm that the system reproducibly returns to the same operating point after a reset.



a) *Current curve during a measurement – clearly visible is the connection and disconnection of the IMU for the system reset*

b) *Current curve after switching on*

Fig. 4.2: Example current consumption during a measurement

4.2. Comparison of power consumption

The evaluation of the power consumption data shows that the start-up phase of the IMU is almost identical across all measurements. During operation, it was found that the power consumption is hardly dependent on the set rotational speed.

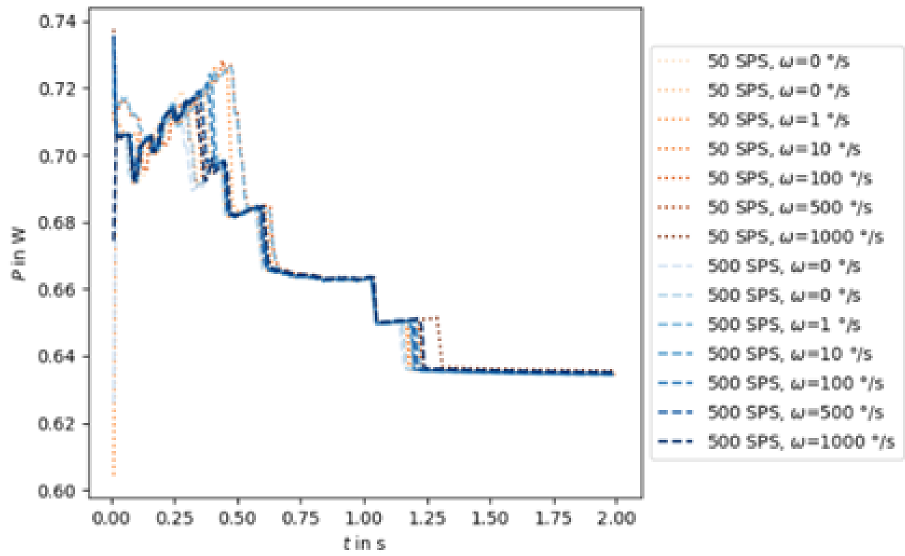


Fig. 4.3: Power consumption during IMU start-up

In contrast, the sampling rate has a significant influence: at higher data rates, power consumption increases measurably. The reason for this is the more intensive communication between sensors and the evaluation unit, which leads to increased energy consumption by the digital interfaces. While mechanical stress has little influence on energy consumption, communication activity is a significant factor.

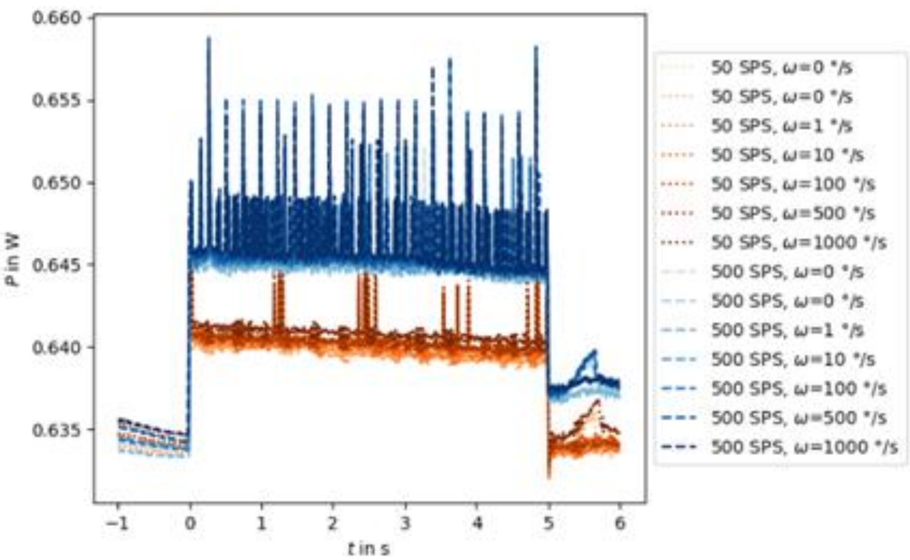


Fig. 4.4: Power consumption curve during the 5-second measurement

4.3. Analysis of sensor data

The recorded sensor data shows the expected behaviour of the individual measured variables. In some cases, minor transmission errors occurred, but these were due to communication problems at high sampling rates and high rotational speeds.

The measured rotation rates in the z-direction correspond linearly to the set rotation speeds of the turntable along this axis. The rotation rates in the x- and y-directions (perpendicular to the axis of rotation) remain constant at 0 °/s, which indicates that the sensor axes are well aligned.

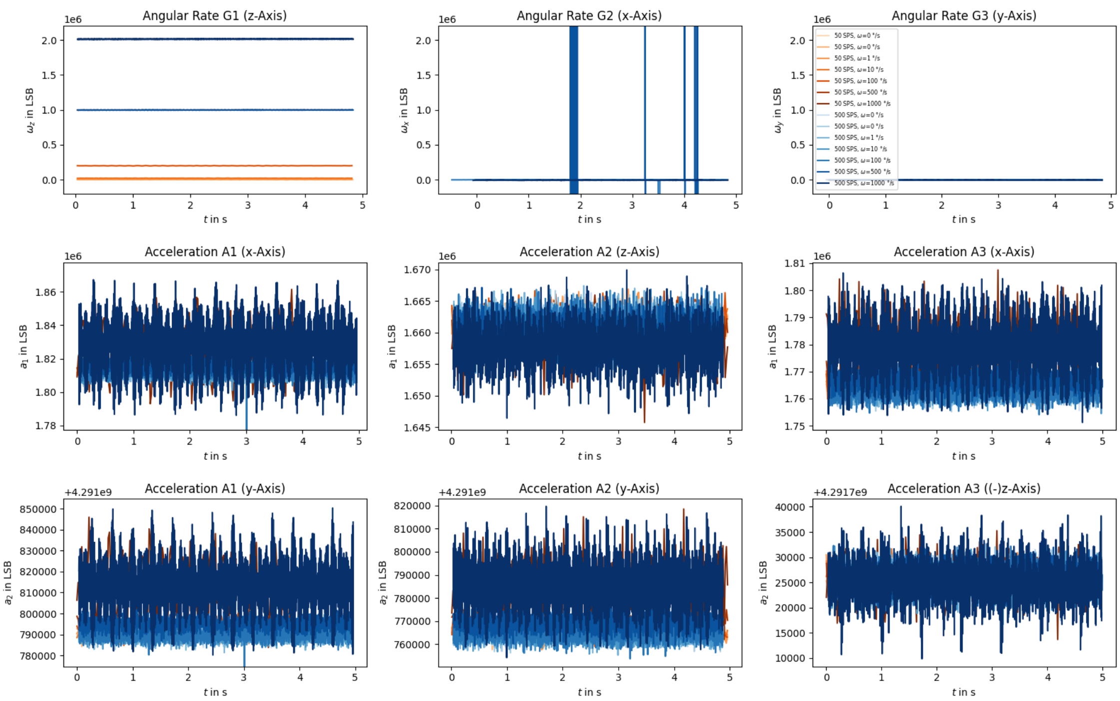


Fig. 4.5: Measurement data for all measurements broken down for each individual measured variable (3xrotation rate, 6xacceleration) presented comparatively

The acceleration values show a slight increase in the x and y directions at higher rotational speeds. This effect can be explained by the centrifugal forces that arise due to a slight eccentricity between the geometric centre of the turntable and the sensor elements. The acceleration in the z direction is not affected by this.

At high speeds, the noise from the acceleration sensors also increases, which is due to vibrations in the turntable system. These effects influence the measurement quality, but not the energy consumption of the IMU itself.

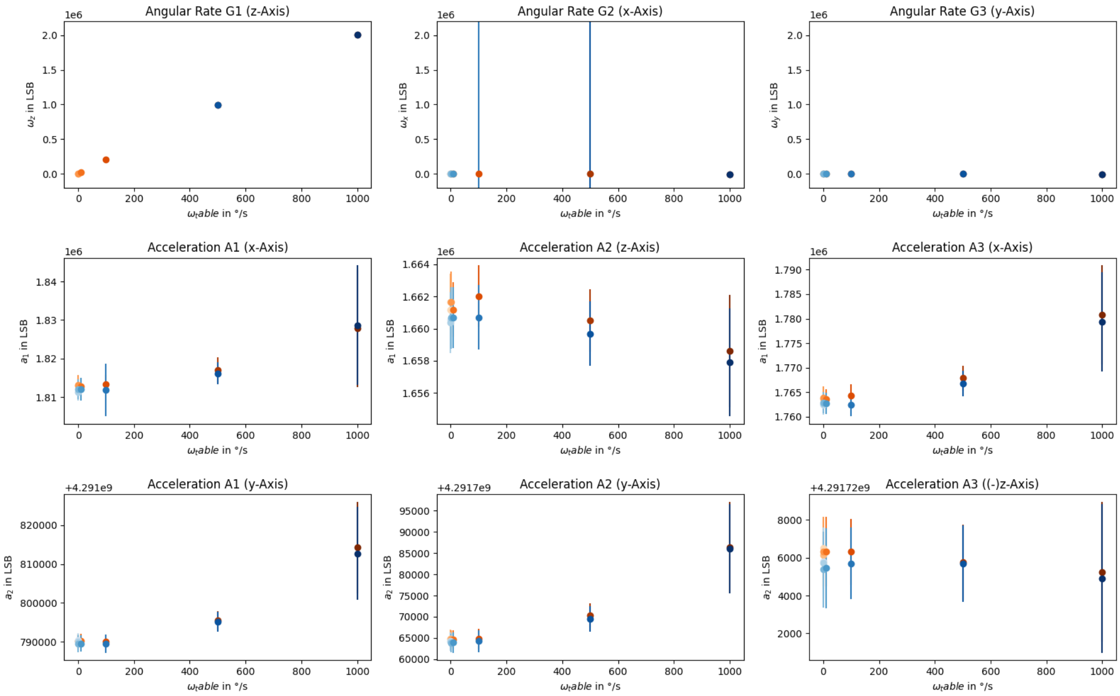


Fig. 4.6: Average values for the respective measurement above the excitation speed (ω_table) shown comparatively for all measured variables (3xrotation rate, 6xacceleration)

The mean values of the measured rotational speeds show a clear linear dependence on the set rotational speed of the turntable. The acceleration values in the x and y directions show a quadratic dependence, which corresponds to the physical relationship between centrifugal acceleration and rotational speed.

Allan variance analysis shows that the accuracy of acceleration sensors can be improved by averaging the measured values. However, this effect is less pronounced for rotation rate sensors at high excitation levels. The measurements also show that noise is higher at lower sampling rates because there are fewer measurement points available for averaging.

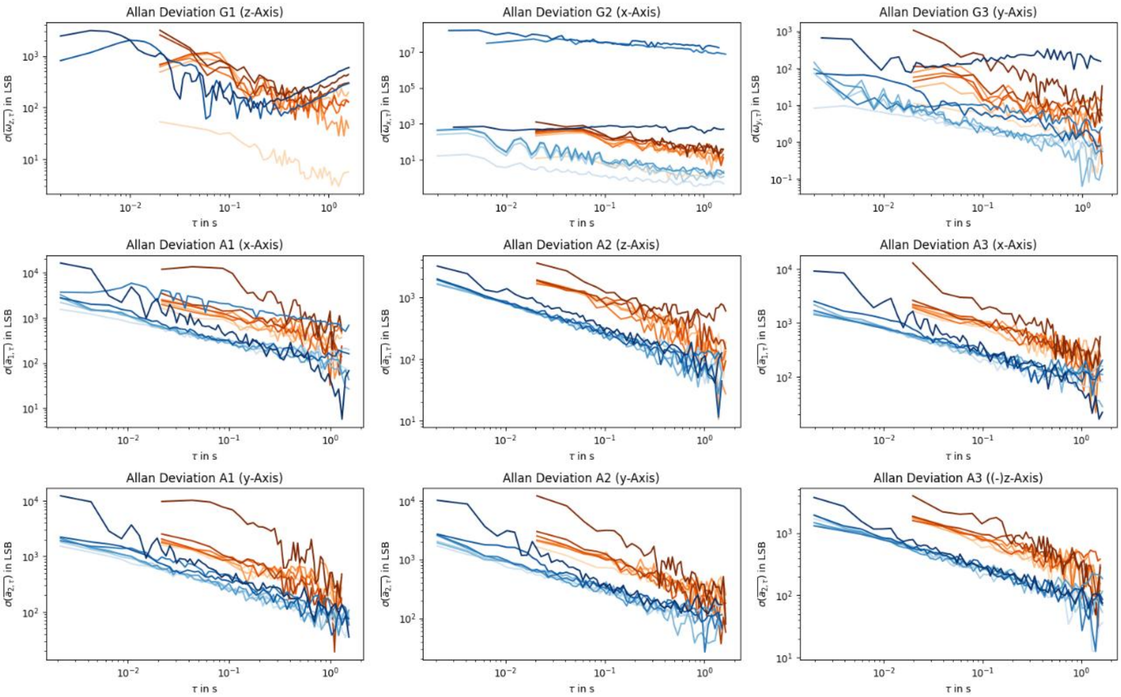


Fig. 4.7: Allan variances of the measurements shown comparatively for all measured variables (3xrotation rate, 6xacceleration)

In the frequency analysis of the sensor data, a clear peak can be seen in the range between 100 Hz and 150 Hz at the highest rotational speed of 1000 °/s. This peak occurs in all measured variables and is attributable to mechanical vibrations of the turntable.

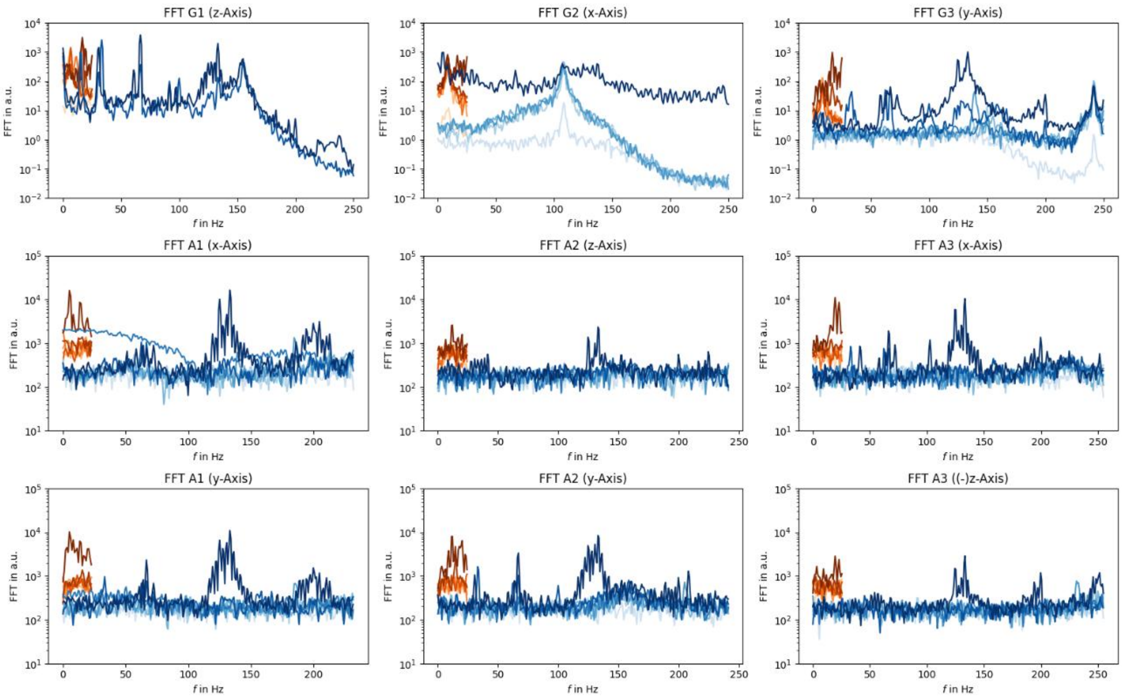


Fig. 4.8: Spectra of the measurements shown comparatively for all measured variables (3xrotation rate, 6xacceleration)

To investigate a possible correlation between rotational speed and energy consumption due to bit distribution in communication, the data transmitted via USB was analysed with regard to the distribution of ones and zeros. No significant trend was found indicating that higher rotational speeds lead to a greater number of ones. After decoding with the COBS (Consistent Overhead Byte Stuffing) method, the number of ones bits actually decreases slightly across all rotational speeds. As expected, the amount of data increases proportionally to the set sample rate. The observed dispersion at high data rates can be attributed to packet loss and faulty transmissions that could not be completely decoded.

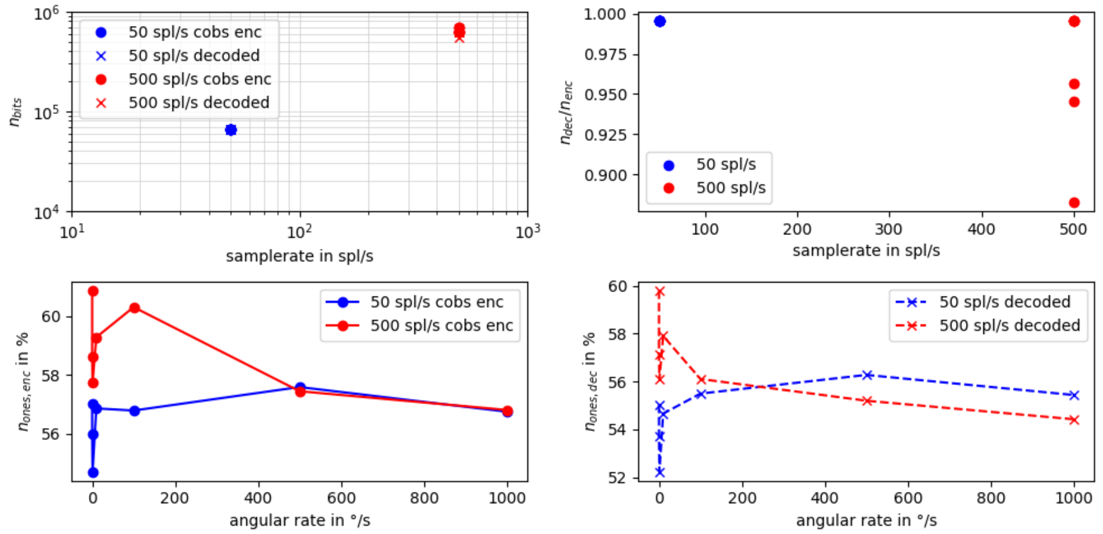


Fig. 4.9: Data analysis regarding the distribution of ones and zeros bits

In order to exclude any possible influence of the sliding contacts at different rotational speeds on energy consumption, an ohmic resistor of 200 Ω was installed instead of the IMU. Figure 4.10 shows the corresponding test setup.

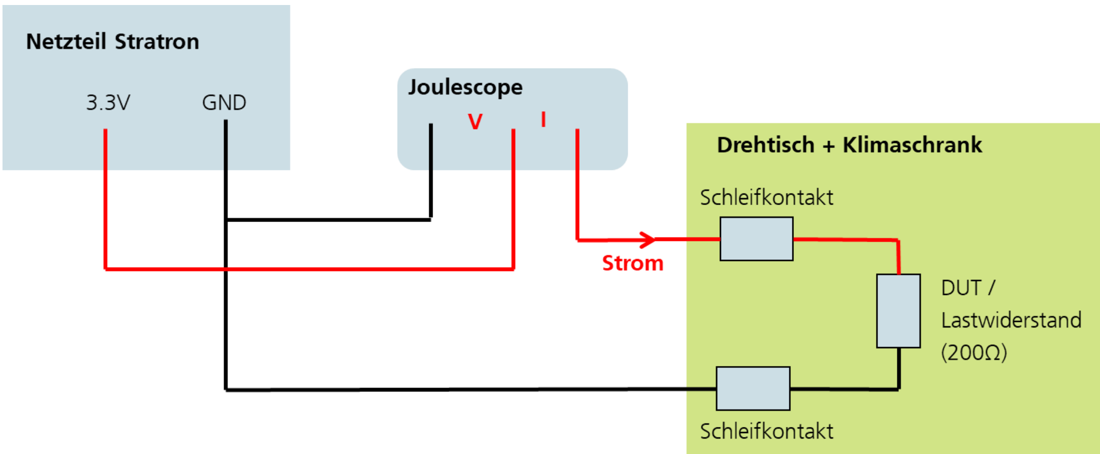


Fig. 4.10: Test setup for investigating the possible influence of the sliding contacts of the turntable

Regardless of the rotational speed, a slight self-heating and associated slight increase in resistance value was observed. However, this does not lead to any relevant additional power consumption.

4.4. Long-term measurement of IMU power consumption

In order to investigate the influence of possible self-heating of the IMU itself, the power consumption was recorded over a period of approximately 1.5 hours. After approximately 1.25 hours, no change in the average power consumption was observed (see Fig. 4.11). However, periodic behaviour was observed: approximately every 30 seconds, the power consumption rose briefly by around 5 mW before slowly decreasing again. This behaviour persisted throughout the entire measurement period and is presumably caused by internal control mechanisms of a voltage regulator. In addition, it was found that the discharge time of these cycles shortened slightly over time, indicating a stable thermal state of the sensor technology.

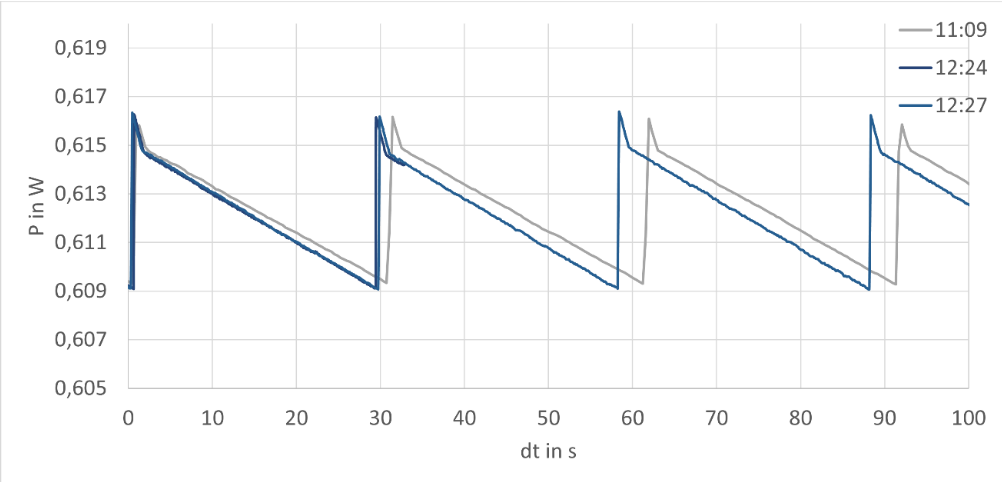


Fig. 4.11: Periodic erratic increases and decreases in power consumption of 5mW

5. Summary and conclusion

The investigations show that the energy consumption of the ENAS-IMU is largely independent of mechanical excitation and rotational speed. However, variations in the sampling rate have a clearly measurable influence: as the data rate increases, power consumption rises due to more intensive communication processes between the sensor and the host system.

Mechanical influences such as vibrations or centrifugal forces primarily affect the measurement quality, but not the electrical power consumption. Tests with an ohmic equivalent resistance show that the test setup does not cause any additional consumption. The brush contacts of the turntable are stable in the high rotation speed range. In addition, long-term measurements confirm stable energy consumption of the IMU with only minimal fluctuations in the milliwatt range, probably caused by a voltage regulator.

6. Recommendations for practical use

The present results show that modern MEMS inertial sensors (IMUs) exhibit high energy efficiency and stability even under typical real-world operating conditions. Several recommendations for practical use can be derived from this:

Optimisation of the sampling rate for energy saving:

Energy consumption depends primarily on the set data rate. Reducing the sampling rate to the minimum actually required can significantly lower power consumption without significantly compromising measurement quality. For battery-powered systems such as drones, wearables or autonomous sensors, this adjustment is a simple and effective measure for extending runtime.

Mechanical influences are energetically negligible:

Rotational speed, vibrations and centrifugal forces have no significant influence on the IMU's power consumption. This makes it robust and reliable for use even in mechanically demanding environments, such as rotating machines, vehicles and robot joints.

Communication interfaces as the main source of energy:

The largest share of energy is used for communication between the sensor and the evaluation unit. Efficiency can be significantly improved through suitable communication strategies such as buffered data transfers, energy-efficient transmission protocols or local pre-processing on the sensor.

Observe long-term operation and periodicity:

Periodic power fluctuations in the range of a few milliwatts may indicate cyclical internal processes (e.g. memory accesses, clock switching, communication cycles or charging processes of voltage regulators). These effects should be taken into account in long-term measurements or energy profile analyses to avoid misinterpretations.

7. Conclusion

In summary, it can be said that modern MEMS inertial sensors have very stable energy consumption, which is primarily determined by software and communication parameters. Mechanical influences (rotational speed/acceleration) mainly affect the measurement quality, but not the electrical power consumption.

In practical terms, this means that IMUs can be used with high reliability even in dynamic or rotating applications without having to worry about energy disadvantages. The greatest leverage for improving energy efficiency therefore lies in optimizing data processing and communication strategies, not in the sensor mechanics themselves.

8. Acknowledgement

This research was funded by the Federal Ministry of Research, Technology and Space (BMFTR) as part of the GreenICT@FMD project (FKZ: 16ME0496).