HIGH-PERFORMANCE ACCELEROMETER APPLICATION IN NAVIGATION, STABILIZATION, CONTROL AND SURVEYING

Wednesday, July 8, 2020
WELCOME TO
High-Performance Accelerometer Application in Navigation, Stabilization, Control and Surveying

Co-Moderator: Lori Dearman, Executive Webinar Producer
Who’s In the Audience?

A diverse audience of over 450 professionals registered from 53 countries, representing the following industries:

- **19%** Military and defense
- **15%** Research
- **11%** University/Education
- **10%** Automotive
- **6%** Transportation, Logistics, Asset Tracking
- **6%** Machine Control, Mining, Construction
- **3%** Precision Agriculture
- **30%** Other
Welcome from Inside Unmanned Systems

Richard Fischer
Publisher
Inside GNSS
Inside Unmanned Systems
A word from the sponsor

Ariane Roller-Vantilcke
Inertial Navigation
Marketing Manager
Thales
Today’s Moderator

Alan Cameron
Editor in Chief
Inside GNSS
PNT Editor
Inside Unmanned Systems
**Poll #1**

What is your status in selection of accelerometer and for which application do you plan to introduce it? (select one answer)

A. In early exploration without any specific application  
B. In R&D & need accelerometer for civil or military airborne apps  
C. In R&D & need accelerometer for land or naval apps  
D. In R&D & need accelerometer for autonomous apps (UAV/auto/train)  
E. Have accelerometer solution & do not plan to change solution

Poll Results (single answer required):

<table>
<thead>
<tr>
<th>Status Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>In early exploration without any specific application</td>
<td>36%</td>
</tr>
<tr>
<td>R&amp;D - need accelerometer for civil or military airborne apps</td>
<td>23%</td>
</tr>
<tr>
<td>R&amp;D - need accelerometer for land or naval apps</td>
<td>10%</td>
</tr>
<tr>
<td>R&amp;D - need accelerometer for autonomous apps (UAV/auto/train)</td>
<td>17%</td>
</tr>
<tr>
<td>Have accelerometer solution &amp; do not plan to change solution</td>
<td>15%</td>
</tr>
</tbody>
</table>
Silicon Accelerometer
MEMS

Vivien Lagorce
MEMS Program Manager
Thales
Thales recognized in high-grade inertial market since 1980

- Embedded in major flagship civil and military programs for 40 years.

- High level of knowledge with more than 1,000 patents

- More than 10,000 navigation product/year and 300,000 MEMS sensors delivered in quartz and silicon technology

- More than 1,5 billions hour of using for MEMS sensors

www.thalesgroup.com
New MEMS Silicon Accelerometer

The best of Thales’s experience to propose a sensor alternative

- A large portfolio with the same sensor size
  - Up to 100g range and 70µg bias
- A very small size for the best performance levels
  - 6cm³
- Easy to integrate
  - Digital SPI interface
- 100% France design and manufacture

<table>
<thead>
<tr>
<th>TopAxyz MEMS family</th>
<th>Ultimate input range</th>
<th>Extended input range</th>
<th>High input range</th>
<th>Standard input range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4000 UR 3000 ExR 2000 ExR 1500 ExR 500 ExR</td>
<td>3000 HR 2000 HR 1500 HR 650 HR</td>
<td>2000 SR 1500 SR</td>
<td></td>
</tr>
<tr>
<td>Input range</td>
<td>&lt;100g 70g 40g</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias (in run)</td>
<td>&lt;40 µg &lt;70 µg &lt;500 µg &lt;1000 µg &lt;4000 µg</td>
<td>&lt;70 µg &lt;500 µg &lt;1000 µg &lt;2000 µg</td>
<td>&lt;200 µg &lt;1000 µg</td>
<td></td>
</tr>
</tbody>
</table>

UR and ExR: under French exportation control
HR: under European dual use exportation control
SR: free of exportation control

www.thalesgroup.com
Thales design choices

- High-sensitivity vibrating beam principle, with differential design for $10^3$ common mode errors rejection
- Manufacturing with only highly stable silicon and silicon oxide materials (no metals), including THALES patent stress isolation features for die assembly
- Custom damping system to improve performance under vibration
Thales design choices

- Force amplification structure
- Resonator drive and Sense electrode
- Damping electrode
- Stress isolation beam
- Anchor
- Guiding beam
- Sensitive axis
- Seismic mass
Designed to be simple to use

- Programmable sample rate up to 6400 Hz
- Single Supply Voltage
- Compensation parameters stored in memory for fast plug and play
- Analog and digital temperature information for compensation
- Calibrated digital speed increment output
- Sinusoidal analog output to be compatible with existing system
- Built-in test for safety critical system and maintainability

**THALES SiA Sensor**
A robust French supply chain

- More than 10 years strong collaboration with Tronics Microsystems
- SiA integration, calibration and acceptance tests performed in Thales facilities
- Product availability and support is guaranteed throughout program lifetime, however long
- Production capacity higher than 30,000/year, with a smart logistic like Vendor Managed Inventory (VMI)
- A robust production line applying APQP international standard
Our expertise in safety and critical applications for your system

- Applying DO254 DAL A aeronautics development methodology to prevent any potential failure

- Thales expertise to support customer during certification process with airworthiness authorities

- Safety and reliability justification to offer lifetime over 25 years and operational failure rate lower than $160 \times 10^{-9}$/h

(*) Under predefined life profile
What choosing Thales means...

Our support from your product development to serial production

- Complete user guide to integrate SiA in your system
- Integration support to help you in your choices
- Engineering support and accessible DO254 data package for certification process
- A calibrated sensor associated to a Certificate of Conformity (CoC) for each sensor
- An enhance logistic and a worldwide support
MEMS History and Market

Dimitrios Damianos, PhD
Technology & Market Analyst
Yole Développement
HIGH PERFORMANCE INERTIAL SYSTEM APPLICATIONS

- Agriculture
- High speed train/Rail maintenance
- UAVs/UGVs
- Structural health monitoring
- Vibration monitoring
- Precision robotics
- Vehicle dynamic testing
- Seismic surveillance
- Pipeline monitoring
- Directional borehole drilling

Industrial

- Maritime navigation
- Platform stabilization
- Gyrocompass
- INS
- AUVs/ROVs
- Freight transport ship
- Antenna stabilization
- Autonomous ships/boats
- Oceanographic & environment monitoring

High end markets

- Commercial Naval

- Commercial Aerospace

Defense

- Defense transport aircraft
- Defense UAVs/UGVs
- Dynamic platform stabilization
- Satcom antenna orientation
- Soldier navigation (Military fighters)
- LAV/Artillery Guns
- MAV/Assault Tanks
- Missile guidance (short, medium and long range)

- Cockpit instrumentation
- AHRS
- Satcom antenna orientation
- Civil aircraft/helicopters
- Small aviation
- Micro-Nanosatellites
- Reusable rockets

- Defense transport aircraft
- Defense UAVs/UGVs
- Dynamic platform stabilization
- Satcom antenna orientation
- Soldier navigation (Military fighters)
- LAV/Artillery Guns
- MAV/Assault Tanks
- Missile guidance (short, medium and long range)

- Commercial
- Naval

- High end markets
ACCELEROMETER DETECTION CLASSIFICATION

- Pendulous/Translational Mass displacement/rebalance
- Resonant Element Frequency
- Thermal Accelerometers
- Quantum sensing
- PIGA
- Force Rebalance Accelerometers
- MEMS
- Resonant Element Accelerometers
- Thermal Accelerometers
- Atom (gravimeter)
ACCELEROMETER PERFORMANCE

Source: Neil Barbour & Yole
15 years ago, MEMS performances were far from high end applications specifications…

Run-to-run accelerometer bias stability

MEMS technologies performances 15 years ago

MEMS accelerometer limit

MEMS gyro limit

1 mg

4 mg

0.35 mg

2005

2015

2020

2025

Run-to-run gyro bias stability

Constant progress of MEMS technology is pushing back the limits and performances. It evolves at a slower pace than expected, however, we do expect some class 1 performances within 5 years.

Class 1

- Land vehicle
- Aircrafts
- Mini UAV
- Guided bomb

Class 2

- Soldiers
- Short-course missiles
- Rocket
- Artillery shell
- Mortar shell
- Binoculars
FOCUS ON SI-MEMS ACCELEROMETER MARKET

High-end* inertial market (industrial, tactical, navigation, strategic)

- All-inertial systems: ~$3.24B
- Si-MEMS accelerometers: ~$200M

Inertial MEMS commercial** market (consumer, automotive, medical)

- All-inertial systems: ~$3.14B
- Si-MEMS accelerometers: ~$1.06B

- All-inertial systems: ~$3.48B
- Si-MEMS accelerometers: ~$1.14B

*High-end: stand-alone accelerometers/gyros, combos IMU/INS etc. All technologies included (Si-MEMS, Q-MEMS, rebalance, FOG, RLG, HRG, DTG etc)

**Commercial: stand-alone accelerometers/gyros/magnetometers, combos (IMUs). Only Si-MEMS technology included.
Ask the Experts Part I
High-Performance Accelerometer Application in Navigation, Stabilization, Control and Surveying

Co-Moderator: Lori Dearman, Executive Webinar Producer
Which class of performance would you be interested in for your applications?

Poll Results (single answer required):

- Bias composite less than 70µg: 41%
- Bias composite between 70µg and 200µg: 31%
- Bias composite between 200µg and 1000µg: 17%
- Bias composite greater than 1000µg: 11%
Usage of High Performance MEMS Accelerometers in Navigation, Stabilization, Surveying and Control
Serving our customers for more than 25 years – worldwide

- Systems for inertial navigation, guidance, surveying and control
- Gyro stabilized platforms – target observation & tracking
- Manufacturing and Development – R&D of ALG, SW/FW, HW, ME
- 75 employees, including 38 engineers ● 18.3 m. € turnover (2019)
- Markets: Surveying, naval / marine, airborne, automotive testing, mining, industrial, defense – manned & unmanned
Main Activities & Areas of Competence

- 1...5 mg
- < 2 mg

- 10...10,000 µg
- 1...500 µg

- 50...500 µg
- 0.1...15 µg

- 10...150 µg
- 1...20 µg

- 10...70 µg
- 0.1...5 µg

accelerometer requirements: day-to-day bias bias instability
Systems using high performance accelerometers

**iIPSC**
Stabilized Gimbals for customized Payloads

**iCORUS**
High accurate Airborne & Shipborne Gravimeters

**iGST / iPST**
Pipeline Surveying and Drillhead Control

**iNAT, iTraceRT, iPRENA…**
INS/GNSS Solutions for Navigation, Stabilization, Surveying & Control
High Performance Accelerometer Requirements

Precise Navigation and Precise Tilt Sensing

- Very low accelerometer bias and also good long time stability of absolute bias (to achieve best system performance and to avoid an unacceptable short recalibration period)
- Very low scale factor error and non-linearity as well as good long time stability
- Very low noise resp. velocity random walk (VRW) to support fast converging of data fusion
- High shock and vibration resistance and immunity (e.g. operation together with RLGs)
- High bandwidth; low and well determined data latency and jitter regarding data sampling
- High stability of mechanical sensor axes (long time misalignment stability)
- Extensive self testing capability / BITE, high MTBF / FIT (reliability)
- Synchronization capability between several sensors, easy interface (SPI) with multiplex capability
Data Fusion („Kalman Filter“): Fusion of Complementary Data to improve the overall accuracy

Optimal Filtering

Image Based Navigation (IBN)
GNSS
Inertial Navigation (INS)
Odometry (ODO)
Any other source

accelerometers
gyroscopes

Most probable Position, Velocity, Attitude, Heading & Standard Deviations

Good starting values (small sensor bias, small scale factor errors etc.) lead to a faster decrease of the standard deviations of the data fusion’s output
Accelerometers: Why low bias is important?

- **lower bias** → better performance even in free-inertial mode
- **lower bias instability** → gives the INS/GNSS data fusion more time / reliability for parameter estimation

- Flat earth: Position error increases **quadratically over time** with accelerometer bias → \( \Delta s = \frac{1}{2} \Delta a t^2 \) → \( \Delta a = 1 \text{ mg} \) → \( \Delta s \text{ (10 s)} = 0.5 \text{ m} \)
  \( \Delta s \text{ (1'000 s)} = 5 \text{ km} \)

- Schuler Oscillation: The free inertial navigation error is damped by the geometry (sphere) of the earth.
  → The gravity is the reason, that the position error does not increase quadratically but only **linear over time**!

- The Schuler amplitude is proportional to the accelerometer offset.
- **The Schuler position error amplitude is about 13 m per 1 µg accelerometer offset.**
- The Schuler period is about 84.4 minutes on the Earth.

  \[ S_{\text{Schuler}} = 2 \frac{\Delta a \gamma_E}{g} \text{ Position amplitude of Schuler oscillation} \]

- Furthermore a gyro bias leads to a Schuler **position drift** of about 60 nm/hr per 1 °/hr gyro bias.
  (simplified explanation)
Accelerometers: Why low noise is important?

lower noise (VRW)  → allows faster parameter estimation within the data fusion

Allan Standard Deviation

<table>
<thead>
<tr>
<th>Sensor</th>
<th>VRW (µg/√Hz)</th>
<th>Bias Instability</th>
<th>Bias (day-to-day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN8 Sia Sensor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QA2000-030 accelerometer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>State-of-the-Art standard nav./AHRS grade MEMS accel.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

New Thales Sia MEMS accelerometer (lab samples):
- VRW: 2 µg/√Hz (< 8 µg/√Hz)
- Bias instability: 1.1 µg @ > 10'000 sec
- Bias (day-to-day): < 70 µg

QA2000-030 accelerometer:
- VRW: 7 µg/√Hz
- Bias instability: 0.3 µg
- Bias (day-to-day): < 70 µg

State-of-the-Art standard nav./AHRS grade MEMS accel.:
- VRW: 20 µg/√Hz (< 50 µg/√Hz)
- Bias instability: 2 µg
- Bias (day-to-day): < 300 µg
Accelerometer: Why low latency and jitter required?

- All implemented accelerometers within the INS shall acquire its acceleration at the same time
- Justification: accurate gravity compensation required during vehicle rotation

\[ \alpha(t_0) \quad \text{[angle of accelerometer against horizon]} \]
\[ \omega \quad \text{[angular rate of INS during time } \tau \text{]} \]

\[ g \approx 9.81 \text{ m/s}^2 \]

- Accelerometer mounted on rotating object
- Assume: rotation rate \( \omega = 200 \text{ °/s} \), pitch = \( \alpha(t_0) = 5 \text{ °} \); unknown delay \( \tau = 1 \text{ ms} \)
- At time \( t_0 \) the gravity \( g \) has to be compensated on the accelerometer with \( g \cdot \sin \alpha(t_0) \)
- If accelerometer data acquisition delay is \( \tau \), the resulting gravity compensation error is
  \[ \Delta a = g \cdot \sin \alpha(t_0) - g \cdot \sin [\alpha(t_0) + \omega \cdot \tau] \]
  **Example:** \( \Delta a (\tau = 1 \text{ ms}) = 3 \text{ mg} \) (e.g., 50 x larger than desired sensor bias!)

- Delay \( \tau \): (deterministic) latency can be corrected if known, but stochastic jitter not!
  \( \rightarrow \) jitter has critical impact on navigation performance – same as fast changing bias!
  \( \Rightarrow \) to achieve < 60 µg accel. accuracy, jitter shall be < 20 µs (Thales SiA:)
Silicon Accelerometer
MEMS

Pierre-Olivier Lefort
MEMS Expert and Product Design Authority
Thales
Sensor characteristics

**KEY PERFORMANCES (MEDIAN VALUES)**

- Acceleration range: Up to 100g
- Bias temperature sensitivity: 12 µg/°C
- Bias (temperature compensated): 0.1 mg
- Scale factor (before/after compensation): 2 ppm/°C - 5ppm
- Vibration rectification: 6 µg/g²
- Noise: [0.01 – 10 Hz] 8 µg/√Hz

**ELECTRICAL INTERFACE**

- Power: 5 Vdc / < 150 mW
- Communication: 3.3 V SPI Full Duplex / Up to 6400Hz sample rate (configurable)

**ENVIRONMENTAL**

- Operating temperature: [-46 ; +90] °C / [-50 ; +195] °F
- Vibration: 15 grms [20 – 2000 Hz]
- Shocks: < 250 g without recalibration

MEMS vibrating beam implementation ➔ navigation grade performances with high input range and robustness
Thermal behavior: better than 50 µg / 10 ppm accuracy

**Stabilized temperature**

Bias residual errors (related to 3rd order temperature model) on 17 sensors over a -40/+85°C range

Mean 20µg

**Variable temperature**

Output variations (µg) vs. Temperature (°C)

Scale factor residual errors on 17 sensors over a -40/+85°C range

Standard deviation mean = 1.7 ppm
Repeatability

- Sensors stored on shelf at 20°C, powered on or off.
- Measurements performed on a regular basis to follow bias and scale factor variations over time.

**Bias stability fully compatible with high grade inertial system requirements**
Allan Standard Deviation for SiA Sensor SN318

- from 4 days recording, 20 Hz sample rate
- lab conditions - 1g static acceleration
- after temperature compensation

![Graph showing Allan Standard Deviation vs. Averaging Time]

Velocity random walk:
2.5 $10^{-3}$ m/s$^2$/h
or 4 $10^{-2}$ m/s$^2$/√Hz

$1/t^{1/2}$
Shock and vibration behavior

Vibration induced error (compensated, in µg)
on 10 sensors, under 12g level random vibrations

Bias variation till 180 shocks with a 180g level along sensitive axis
Our silicon technology

- Manufactured from a 150mm silicon wafer with high accuracy DRIE etching
- A 60 µm thick active layer with low resistivity, within a 3 layers assembly
- Layers assembly with silicon oxide obtained by high temperature silicon bonding

From wafer to chip using high-end processes
SiA sensor can be mounted with connector up or down relative to the mounting plane chosen using 2 M2 screws.
Electronic integration – Analog sensor vs. SiA

**Analog sensor**
- ~70gr / ~30 cm³
- Pendulous Rebalance
- Power supply: ±13 V to ±28 V, < 480 mW

**SiA sensor**
- < 20gr / < 6 cm³
- Power supply: 0-5V, < 150 mW

**Digital information**
- High resolution (>16 bits)
- Analog-to-digital converter (ADC)
  (ex: 1µg for 100g range = 26 bits)
- > 50 mW (x3 in IMU)
- SPI bus

**SiA sensor**
- SiA
- Power supply: 0-5V, < 150 mW

**Microcontroller (or FPGA)**
- ±10V
- SPI bus
- (32 bits output, LSB ~ 1 µm/s² - 0.1 µg)
- Including Cyclic Redundancy Check (CRC) for correct data communication
Synchronisation

RTC (Real Time Clock) configurable by the user

Speed increment delivered at RTC rising edge frequency

RTC sampling frequency can be defined by the user or generated inside the SiA sensor

Latency 400 µs +/- 30 µs
(for 6400 Hz RTC including 50µs SPI transmission duration)

1 master, 2 slaves

3 slaves
Reliability assessment

Functional & design analysis: from device functions, failure modes identification & classification through criticality analysis.

- Reliability assessment plan for each sub-assembly and SiA product
- Reliability quantitative evaluation for different mission profiles

### Packaging
- 2 years 85°C storage (x4)
- 500 thermal cycles -40/95°C (x3)

### MEMS Cell
- 1 year 85°C storage (x24)
- 1 year 150°C storage (x8)
- 1000 thermal cycles -40/95°C (x8)

### Electronics

- Failure rate estimated to 30 $10^{-9}$/h using FIDES approach (*)
- (*) for long range aircraft mission profile

- IBIT: Initial Built-In Test
  Available upon user’s request (checking of the sensors functionality: seismic mass check and MEMS resonators behavior check).

- CBIT: Continuous Built-In Test
  Covering out of range acceleration input, out of range resonators frequencies, CRC errors, Internal bias voltages control, oscillator loop parameter check.
**Quick Poll**

**Except for performance, what is the other key requirement your accelerometer should have?**

Poll Results (single answer required):

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small size</td>
<td>39%</td>
</tr>
<tr>
<td>Easy to communicate (SPI)</td>
<td>23%</td>
</tr>
<tr>
<td>Without exportation constraint</td>
<td>24%</td>
</tr>
<tr>
<td>Civil Certification data package (DO254)</td>
<td>7%</td>
</tr>
<tr>
<td>Large portfolio for a same size of sensor</td>
<td>6%</td>
</tr>
</tbody>
</table>
Ask the Experts Part II
High-Performance Accelerometer Application in Navigation, Stabilization, Control and Surveying

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