The Promise of MEMS to The Navigation and Mobile Mapping Community

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ION California Chapter
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Agenda

- Progress of the RF Technologies
- Forces driving the development of Integrated Navigation Systems
- Mobile Mapping Systems (MMS)
- The Potential of MEMS Sensors
- Sensors and Integration Problems
- Achievable Accuracies for Machine Control and PNS
- Potential for Airborne MMS
- Summary
RF Positioning Technologies

Position Yourself Ahead of the Crowd

GNSS
- GPS
- GLONASS
- Galileo
- QZSS
- COMPASS
- IRNSS

Alternatives to GNSS
- Cellular Technology
- Wireless Sensor Networks

GNSS + Wireless Technologies
- Assisted GPS
- Enhanced GPS
- Bluetooth
- Ultra Wide Band
Impact of GNSS Revolution on The User Community

With the increased number of satellites and more sophisticated GNSS receivers, users will be able to operate in a wider range of conditions and applications.
The current market in positioning and navigation is clearly dominated by GPS. Besides being globally available, it provides the whole range of navigation accuracies at very low cost. It is also highly portable and has low power consumption.

At this point in the development of navigation technologies, the need for alternative positioning systems only arises because GPS does not work in all environments.

With current GPS receiver chips reaching unit price of about $5 and the predictions are that it will drop to about $1 in few years, most likely, it will level off.

Considering these price projections, is there any POS/NAV technology that is competitive with GPS?

At this point the answer is clearly in the negative.

Therefore, other navigation technologies would typically be developed for 'non-GPS' environments and/or to complement GPS.
Forces Driving the Development of Integrated Systems

- **Category 1: GPS does not work everywhere as a stand-alone system**
  - The need for non-GPS solutions in certain scenarios (e.g. inside buildings)

- **Category 2: Market Demand**
  - Large market share and explosive growth predicted for smart phones and intelligent transportation systems

- **Category 3: New Application**
  - E.g. - Machine Control and Direct Geo-referencing of Mapping Sensors

- **Category 4: Military Specifics**
  - The need for autonomous navigation systems
Example of Category 3: Land MMS

Digital Cameras

GPS

INS
Land MMS - Visualization Applications

- Enhanced internet viewing, search and visualization
Land Based MMS

- Example – VISAT™
  - Navigation-grade INS
  - Dual-frequency GPS
  - Van
  - Computer, 8 cameras, etc.
  
  - $100,000 (30% of budget)
  - $20,000
  - $30,000
  - $$$

> $300,000

*Widespread adoption of current systems has been limited by their high cost*
Inertial Technology

INS
Ltn-100G
Error Compensation
80-100K USD
Navigation Computer

IMU
Ltn-200
Error Compensation
20-60K USD

BEI-DQI ISA

Price

Accuracy

Navigation + Corrected Raw Inertial Data

Corrected Raw Inertial Data

Raw Inertial Data

www.geomatics.ucalgary.ca
Roadmap of Inertial Technology

<table>
<thead>
<tr>
<th>Size/Price</th>
<th>Nav</th>
<th>Tactical-I</th>
<th>Tactical-II</th>
<th>Consumer</th>
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<tbody>
<tr>
<td>- 1980</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Now</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Micro-Electro-Mechanical Systems (MEMS)

www.geomatics.ucalgary.ca
MEMS is an enabling technology with a massive global market volume worth $12 billion in 2004 and is expected to reach $26 billion in 2010 [Source: NEXUS Market Analysis for MEMS and Microsystems].

This means that it will have about much larger than the market size of GPS at that time.

A small portion of this market, however, will support inertial sensor technology.

Yole Development estimated that the world markets for MEMS-based inertial sensors have reached almost $0.7 billion in 2004 and will exceed $2 billion in 2010.

The major growth opportunities will come from automotive and consumer markets (Smart Phones).
Performance of Gyro Technologies is usually described by the bias and scale factor stability.
MEMS IMU - An Example

UofC IMU - Developed by employing off-the-shelf MEMS sensors with an average sensor cost 60$

- Advantages
  - Low cost
  - Small size
  - Low power

- Disadvantages
  - Large bias and SF error
  - Thermal drift

<table>
<thead>
<tr>
<th></th>
<th>ADI Gyro (ADXRS150EB)</th>
<th>ADI Accel. (ADXL105A)</th>
</tr>
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<tbody>
<tr>
<td>Range</td>
<td>± 150 deg/s</td>
<td>± 5 g</td>
</tr>
<tr>
<td>Cross-axis</td>
<td>± 1 deg</td>
<td>± 1 deg</td>
</tr>
<tr>
<td>Sensitivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bias error</td>
<td>± 24 deg/s</td>
<td>± 2500 mg</td>
</tr>
<tr>
<td>Bias instability</td>
<td>0.01 deg/s</td>
<td>0.2 mg</td>
</tr>
<tr>
<td>(100 sec) *</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scale factor</td>
<td>± 10%</td>
<td>± 10%</td>
</tr>
<tr>
<td>error</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price**</td>
<td>USD 10</td>
<td>USD 2.5</td>
</tr>
</tbody>
</table>
MEMS IMU - Lab Calibration

- Bias
- Scale factor
- Cross-axis

Error Model for Calibration (Gyros)

\[
\begin{bmatrix}
U_x \\
U_y \\
U_z
\end{bmatrix} =
\begin{bmatrix}
k_{xx} & k_{xy} & k_{xz} \\
k_{yx} & k_{yy} & k_{yz} \\
k_{zx} & k_{zy} & k_{zz}
\end{bmatrix}
\cdot
\begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix} +
\begin{bmatrix}
U_{0x} \\
U_{0y} \\
U_{0z}
\end{bmatrix}
\]

Effects of calibration

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>&lt; 25 deg/s</td>
<td>&lt; 0.5 deg/s</td>
</tr>
<tr>
<td></td>
<td>&lt; 2500 mg</td>
<td>&lt; 6 mg</td>
</tr>
<tr>
<td>Scale Factor</td>
<td>&lt; 10 %</td>
<td>&lt; 0.1 %</td>
</tr>
<tr>
<td>Cross-axis</td>
<td>&lt; 1.0 deg</td>
<td>&lt; 0.2 deg</td>
</tr>
</tbody>
</table>
MEMS Enabled New Applications - UofC Collar
MEMS Enabled New Applications - PNS

- GPS Antenna
- Memory card
- Magneto-meters
- Gyro Modules
Portable MMS

3-D coordinates

Position
- Latitude: 39° 44' 25.90"
- Longitude: 104° 59' 26.95"
- Ellip. Height: 1576.76 m
- North: 4398959.14 m
- East: 500786.70 m
- Ortho: 1576.76 m
- Parallax: 0.0398
- Precision: 0.11 m

Anchor 1: 68.00 X 170.00 Distance 10.47 m

Anchor 2: 419.50 X 211.00 Distance 8.08 m

Image 1

Image 2
GPS/INS Integration

- Combining INS & GPS signals
  - Kalman filter typically used (optimal if certain assumptions are met)
  - Many integration strategies (loose, tight, deep)
- Filtering and prediction for the loose EKF (15 or 21 state):

\[
x = \begin{bmatrix}
\delta P_{1x3} & \delta V_{1x3} & \delta A_{1x3} & \delta \omega_{1x3} & \delta f_{1x3} & \delta SF \omega_{1x3} & \delta SF f_{1x3}
\end{bmatrix}^T
\]
Problems with MEMS Sensors

- Most of the inadequacies are related to the sensors performance:
  - MEMS-based inertial sensors suffer from relatively poor signal to noise ratio (i.e. high noise level).
  - MEMS-based inertial sensors experience high thermal drift characteristics that may jeopardize the overall accuracy of the navigation systems.
  - MEMS-based inertial sensors have a significant run-to-run bias instability terms.
- The net effect is that the accuracy of a stand alone MEMS-based INS will deteriorate very quickly during GPS signal outages.
Example: A MEMS-based gyro along the vertical direction – theoretical measurement = $\omega_e \cos(\varphi)$

$\omega_z$ (deg/hr)

$\omega_e \cos(\varphi) = 15.04 \cos (51) = 11.67$ deg/hr

150 deg/hr variation in 100 second
Comparison to a Tactical Grade Gyro Performance

\[
\omega_e \cos(\phi) = 15.041 \text{deg} \cos(51) = 11.67 \text{deg/hr}
\]
Problems with MEMS Sensors

- Example: A MEMS-based Accelerometer along the vertical direction

\[ f_z \left( \frac{m}{sec^2} \right) \]

Bias = 50 mg

Time (Sec)
Problems with MEMS-based INS/GPS

- Comparison to a Navigation Grade Accel

\[ f_z \left( \frac{m}{sec^2} \right) \]

Bias = 100 \( \mu g \)
Effect of Inertial Sensor Errors on Navigation Parameters

- An uncompensated accelerometer bias error will introduce:
  - An error proportional to t in the velocity
  - An error proportional to $t^2$ in the position.

\[
v = \int b_f \, dt = b_f \, t \iff p = \int v \, dt = \int \int b_f \, t \, dt = \frac{1}{2} b_f t^2
\]

Error in position due to an uncompensated accelerometer bias of 100 $\mu$g ($10^{-4}$ g $\approx$ $10^{-3}$ m/sec$^2$) can introduce positional error in 60 sec $= \frac{1}{2} \times 10^{-3} \times (60)^2 = 1.8$ m
Effect of Inertial Sensor Errors on Navigation Parameters

- An uncompensated gyro bias (usually expressed in terms of deg/h or rad/s) in the X or Y gyro will introduce errors in roll or pitch proportional to time $t$.
- This small angle will cause a misalignment of the INS, and therefore a projection of the acceleration vector in the wrong direction.

\[
\Delta \theta = \int_0^t \Delta \omega \cdot d\tau = \Delta \omega \cdot t
\]

\[
\Delta v = \int_0^t (g \cdot \Delta \theta) \cdot d\tau = \int_0^t (g \cdot \Delta \omega \cdot \tau) \cdot d\tau = \frac{1}{2} \cdot g \cdot \Delta \omega \cdot t^2
\]

\[
\Delta r = \int_0^t \Delta v \cdot d\tau = \int_0^t \left( \frac{1}{2} \cdot g \cdot \Delta \omega \cdot \tau^2 \right) \cdot d\tau = \frac{1}{6} \cdot g \cdot \Delta \omega \cdot t^3
\]

Assume a GS signal outage of half minute and the gyro bias error of 0.01 deg/s, then will lead to positional error as follows:

\[
\Delta r = \frac{1}{6} \cdot 9.81 \cdot \left( 0.01 \times \frac{\pi}{180^\circ} \right) \cdot 30^3 = 7.7m
\]

\[
\sqrt{2} \cdot \Delta r = \sqrt{2} \times 7.7m = 10.9m
\]
Possible Improvement of MEMS Sensor Performance

- Multi-level Wavelet Decomposition:

  ![Multi-level Wavelet Decomposition Diagram]

  - Inertial Navigation Algorithm
  - Integration Algorithm (Kalman Filtering)

  Position Velocity Attitude
Multi-level Wavelet Decomposition:
Possible Improvement of MEMS Sensor Performance

- De-noising Inertial sensor signal utilizing Multi-level Wavelet Decomposition:

Inertial Sensor Measurement

- A1
- D1
- A2
- D2
- A3
- D3
- A8
- D8
Wavelet De-noising – Z Gyroscope Measurements

Raw Z Gyro Measurements

De-noised Z Gyro Measurements - 7th Level Approx.
Problems with MEMS Sensors

Raw measurements of the Z-axis Accelerometer

Z-axis Accelerometer after wavelet de-noising (level 5)

Extracting the thermal trend of Z-accelerometer output using Wavelet de-noising
MEMS: filter tuning issues

- The same MEMS inertial sensor coming off the same production line may have very different error behaviors than other similar sensors.
- Individual sensors need individual error characterizations that cannot be performed ahead of time due to cost restrictions.

1. A priori information difficult to obtain

2. The problem of high production
Possible Ways to Improve the Positional Accuracy?

- Improving the performance at the integration filter level
  - Use of velocity aiding in body frame
    - Zero Velocity Update (ZUPT) when possible
    - Non-holonomic constraints
    - Odometer
  - Advanced Algorithm
    - Unscented Kalman filter (UKF)
    - Integration of EKF/UKF and Artificial Neural Network (ANN)
  - Hands off online approach to tuning after the unit is deployed, with ability to change over time. Also leverage tuning information of one sensor to others for improved results for similarly manufactured sensors.
Achievable Accuracy

Inertial Systems
- Honeywell CIMU (Reference System)
- ADI - UofC
- Low cost IMU ($200)
- Few MEMS sensors

GPS
- NovAtel OEM4
- NovAtel OEMStar
- UbBlox (HSGPS)
- Commercial Dual GPS Heading System

Nav Aid
- Mags
- Baro
Frequent GPS outages (10 – 60 sec)
Test Environment

Long GPS outages (200 sec)
Test Environment

Urban Canyon GPS signal blockage and multipath (Downtown) Distance = 3km; Time = 10 min
Hardware used:

3 MEMS Gyroscopes
- 1.26 deg drift in 30s period (3 sigma)
- BOM = $75 each axis

3 MEMS Accelerometers
- 0.2 mg bias instability
- BOM = $20 for all three axes

2 GPS receivers/antennas
- No multipath mitigation
- BOM = $100 for 2 receivers + antennas
Heading Performance (Overall)

- Overall heading std = 2.0 degrees
- Maximum heading error = 9.3 degrees after 10 minutes w/out GPS

Effect of multipath on the carrier phase derived GPS heading is very obvious.
HEADING PERFORMANCE WITHOUT GPS

Maximum heading error = 9.3 degrees after 10 minutes w/out GPS
Positioning in Downtown

Average position error = 8.1 meters
Maximum position error = 134 meters after 10 minutes w/out GPS
Personal Positioning Status

• Reliable, accurate and cost effective personal positioning is not available

- GNSS not always available or is unreliable (multipath)
- Wireless infrastructure is limited
- High end INS/GPS systems are too expensive

Where now?
1. **Accelerometers**
   - Typically 3D, as cost is not an issue (<$4 in quantity)
   - 1200 mGal (Gal = 0.01 m/s²) bias instability, 0.3 m/s/sqrt(hr) VRW

2. **Gyroscopes**
   - Drives the price of the overall BOM. Using lowest cost gyros (~$7/axis)
   - Less expensive per axis if bought in dual package (~$10 for 2D)
   - 150 deg/hr bias instability, 6 deg/sqrt(hr) ARW

3. **Magnetometers**
   - Typically 3D, as cost is not an issue (<$2 in quantity)
   - Prone to magnetic effects: in urban centers may be able to use less than 50% of the data from magnetometers but…
   - With intelligent processing they can be very useful

4. **Barometers (pressure)**
   - Can be very useful for urban navigation (<$4 in quantity)
   - Do not exist in many mainstream consumer devices
Maximum position error = 1.3Km meters after 2 minutes w/out GPS
Maximum position error = 30m meters after 2 minutes w/out GPS
### HSGPS Scenario BOM

<table>
<thead>
<tr>
<th>Scenario</th>
<th>BOM ($)</th>
<th>Availability (%)</th>
<th>Mean overall position error (m)</th>
<th>Max position error (m)</th>
<th>Downtown position std (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS only</td>
<td>6</td>
<td>79</td>
<td>9.5</td>
<td>177</td>
<td>29.2</td>
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</tbody>
</table>
### Scenario BOM ($) Availability % Mean overall position error (m) Max position error (m) Downtown position std (m)

<table>
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<tr>
<th>Scenario</th>
<th>BOM ($)</th>
<th>Availability %</th>
<th>Mean overall position error (m)</th>
<th>Max position error (m)</th>
<th>Downtown position std (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G3A+mag (no TPP)</td>
<td>18</td>
<td>100</td>
<td>31.6</td>
<td>1399</td>
<td>30.6</td>
</tr>
<tr>
<td>1G3A+mag (with TPP)</td>
<td>18</td>
<td>100</td>
<td><strong>16.4</strong></td>
<td>256</td>
<td><strong>27.4</strong></td>
</tr>
</tbody>
</table>

© Trusted Positioning Inc.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>BOM ($)</th>
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<th>Mean overall position error (m)</th>
<th>Max position error (m)</th>
<th>Downtown position std (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU+mag + baro (no TPP)</td>
<td>31</td>
<td>100</td>
<td>13.7</td>
<td>417</td>
<td>32.2</td>
</tr>
<tr>
<td>IMU+mag + baro (with TPP)</td>
<td>31</td>
<td>100</td>
<td>13.5</td>
<td>195</td>
<td>27.7</td>
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</table>
MEMS BS with Velocity Constraints

- Major improvement with average positional error in the 2 m level
Low Cost Airborne MMS

- Right of Way (ROW) mapping/monitoring of remote areas
- Minimal cost through the utilization of low cost components
- Operate without ground work → Lower cost

(C) Intermap
Inertial Systems Setup

Kodak DCS 14N (4536 x 3024 pixels)

LN200

UofC MEMS IMU
### Error Statistics (deg)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
<td>0.0</td>
<td>-0.75</td>
<td>1.21</td>
<td>0.28</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.0</td>
<td>-1.15</td>
<td>1.07</td>
<td>0.44</td>
</tr>
<tr>
<td>Heading</td>
<td>0.2</td>
<td>-2.5</td>
<td>3.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

- The LN200/DGPS solution has been used as a reference.
- The alignment of the MEMS IMU is based on static levelling (for roll and pitch) and 5-7 minutes on-the-fly alignment for heading estimation.
- The average misalignment between the MEMS IMU and the LN200 (0.2, 0.3, and 1.2 deg) was removed when computing the mean values.
- Promising results for Integrated Sensor Orientation.
Summary

1. MEMS inertial navigation has shown promising performance today.
2. It will keep improving with the fast upgrading of the MEMS sensors in the market. The cost of the systems is also expected to drop down quickly with the blooming sensor manufacture.
3. Testing of MEMS-based IMU/GPS system with auxiliary velocity update can reach the requirements for land vehicle navigation and land based MMS systems.
4. Promising potential of using low-end MEMS inertial sensors for machine control, PNS, and airborne MMS (e.g. Right of Way (ROW) of highways and Oil&Gas pipelines)

With the technology push and the market pull, MEMS inertial systems is going to reach the performance of Tactical Grade IMU soon.