Inertial sensing using cavity optomechanics

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Prof. Peter Barker

University College London

Cambridge Wireless event
‘What’s a nanosecond between friends?’
1st May 2019
Preface

| I won’t be talking about clocks 😞 |

| My work is on inertial sensors that REQUIRE commercial (+ cheaper) timing |

| My inertial sensors can HELP commercialisation of state-of-the-art clocks & clocks on-the-move |

I’m your customer + co-technology supplier
Motivation

- Global navigation satellite systems (GNSS) enable positioning:
  - weakened in dense urban environments
  - unavailable indoors/underground/underwater
  - compromised in hostile areas
- During GNSS deadtime, use sensor fusion + local clock:
  - Positioning, navigation & timing (PNT) solution:
    - local clock + IMU (accelerometers + gyroscopes)

GNSS signal “It’s like a car headlight 20,000 kilometres away”
David Last, former president of Royal Institute of Navigation

A simple but not complete solution for PNT
Contents

- Commercially feasible improvements to navigation
  - consumer vs. state-of-the-art
  - building block & co-technology for new technologies

- Cavity optomechanics for motion sensing
  - whispering gallery mode (WGM) optical IMU
  - prototyping & field-testing a WGM accelerometer

- WGM positioning, navigation & timing: a UK consortium?
  - compatibility with NPL’s WGM optical atomic clock
  - chip-compatible fabrication
Commercialising navigation

<table>
<thead>
<tr>
<th>Consumer PNT (£10 per device): i.e. indoor navigation</th>
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<tr>
<td>- commercial IMUs have too much drift &amp; noise</td>
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<td>(usable for minute)</td>
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<td>- timing is not the bottleneck but clocks too expensive</td>
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![Graph showing position error over time](image)

Double integration of accelerometer noise with perfect timing accuracy still leads to error.

| Requirement: IMU of same size, weight, power consumption & cost but 100x improved performance |
Commercialising navigation

- State-of-the-art PNT (£100k’s per device): i.e. space/military navigation
  - new generation of IMUs + clocks being developed
  - quantum cold atom systems require co-technology
    i.e. fill data in between samples, stabilisation
  - co-technology needs to be cheaper & smaller
Importance of co-technologies

“The Washington detector sometimes picked up noise from the wind, as little as 20 or 25 miles per hour.

Things were even worse in Louisiana, where trains and a nearby logging operation constantly shook the ground during the day.

…After the upgrade, the two instruments now have active vibration isolators: Seismometers pick up tiny ground vibrations and motors automatically push to cancel them out—like how noise-cancelling headphones get rid of background noise.”
# Improving inertial sensors

## Performance metrics (test-mass on spring IMUs):

<table>
<thead>
<tr>
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<th>Signal-to-noise</th>
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<td>Thermomechanical noise</td>
<td>Vibration rectification error</td>
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<td>Test-mass</td>
<td>Scale-factor magnitude</td>
<td>Shock/damage threshold</td>
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<td>Scale-factor non-linearity</td>
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## Performance improvement:

- closed loop operation
- mechanical design change
- change of transduction method
# Improving inertial sensors

## Performance metrics:

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## Performance improvement:
- **closed loop operation** + **temperature stability**

## Commercial effort:
- Software optimisation or “off-the-shelf” solutions & PID control
- Still depends on detection noise level

*Low commercial effort*
Improving inertial sensors

| Performance improvement: mechanical design change |
| Commercial effort: |
- Limited applications due to decreased operating bandwidth?
- Expensive changes to existing fabrication processes
- Still depends on detection noise

A BROAD-BAND SILICON MICROSEISMMETER WITH 0.25 NG/RTHZ PERFORMANCE

W. T. Pike¹, J. M. Standley², S. B. Calcutt³ and A. G. Mukherjee⁴
¹Department of Electrical and Electronic Engineering, Imperial College London, London, UK
²Kinematics, Pasadena, California, USA
³Department of Physics, University of Oxford, UK

Medium commercial effort but larger size sensor
Improving inertial sensors

- Performance improvement: **change in transduction method**
  - Low noise signal (i.e. suppressed to quantum fluctuations)
  - Enhanced coupling btn signal & motion (i.e. resonant amplification)

\[
\delta \theta_a = 4\pi \frac{\delta x}{\lambda}
\]

\[
\delta \theta_b = 2\frac{c}{L\kappa} \delta \theta_a
\]

- Commercial effort:
  - Keep existing micro-electro-mechanical systems (MEMS) designs
  - Integrate commercial telecoms photonics
Cavity optomechanics

- Coupling between mechanical motion & optical resonance
- Resonance condition affected by motion of cavity - can reach $10^{-18}$ m/Hz$^{1/2}$
- Strength of coupling (i.e. GHz/nm) depends on resonance losses

LIGO (Credit: National Science Foundation)

Levitated nanosphere within cavity, Prof. Barker
Spherical cavities

- Sphere confines light via total internal reflection to create whispering gallery mode resonances (WGMs)
- Evanescent field (light beyond surface)
- Evanescent waveguide couples light into WGM at separation $d_0$ (~ 100's of nm)
- Tune the laser frequency to find WGMs – seen as dip in the transmission
WGM Transduction

Response to $d_0 + \Delta y$: shifting of WGM + additional broadening

Microsphere-cantilever
- detect thermal Brownian motion (sensitivity $10^{-12} \text{ m/Hz}^{1/2}$)
Closed loop control

Control & damp the thermomechanical energy
Motion becomes indistinguishable from white noise

Y. L. Li, J. Millen & P.F. Barker, Optics Express, 24 (2) (2016)
WGM Accelerometer

| Acceleration: $d_0 + \Delta y$ where $\Delta y$ proportional to acceleration due to Newton’s 2\textsuperscript{nd} Law of motion & Hooke’s Law

| Currently: detect micro-g ($g=9.81\text{ms}^{-2}$)
  - Noise density of micro-g/Hz\textsuperscript{1/2} ($\sim0.0006 \text{ms}^{-1}/\text{Hr}^{1/2}$, $\sim1$ mGal)
  - Already high performing for gravity mapping applications
WGM inertial measurement unit

Accelerometer: bandwidth defined by fundamental mechanical freq.
Gyroscope: vibratory gyroscope* operating at second mechanical freq.

Rate of rotation = amplitude of motion at 2\textsuperscript{nd} mechanical frequency

* Alternative WGM gyroscope: Pascal del’Haye at NPL working on Sagnac WGM gyroscopes
Accelerometer prototype

- portable prototype
- battery powered
- automated system using FPGA
- no monitors/screens
- no vacuum required

Learning the basics of systems engineering within 1 year
Accelerometer testing

- For single vibration:
  - high linearity (<0.2%)
  - great cross-correlation (r=0.997)

Outdoor testing on “Jackal”: deviation from linear at some frequencies due to mounting & housing, requires more active temperature control. BUT functional at ± 60g

Y.L. Li & P.F. Barker, Sensors, (DOI: 10.3390/s18124184)
Y. Lia Li & P.F. Barker, Journal of Lightwave Technology (DOI: 10.1109/JLT.2018.2853984)
Next stage...

| Hand-fabricated sensor already performs well
| - micro-electro-mechanical system (MEMS) will be even better! Aim towards 10’s ng/Hz$^{1/2}$ with reduced bias errors
| - we need help – MEMS is not our expertise

| Currently using photonic MEMS via traditional semi-conductor processes (MPW)

| WGM gyroscope in development
| Aim towards 0.01° /Hr$^{1/2}$

| WGM PNT? Patent 2017

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11:45pm ‘High-performance MEMS oscillators for timing and inertial measurement systems’ Prof. Ashwin Seshia

Photo: Mark Oxborrow
UK PNT Infrastructure

| Complete WGM PNT can be produced rapidly through collaboration
| - WGM frequency comb + atomic gas cell = optical atomic clock
  See Pascal del’ Haye’s work at NPL

| Industry engagement is required
| - Quality assurance testing
| - Noise suppression & algorithms
| - Sharing of IP

| DARPA spending ~ $B’s into PNT
Thanks!

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