MAS836 – Sensor Technologies for Interactive Environments

Lecture 8 – Inertial Sensors

Readings…

There are many posted on the website.

Inertial Sensing

- Measures the inertial properties of a body – i.e. those having to do with dynamics (time derivatives of coordinates)
  - Exploit only the properties of objects moving in space (F=ma)
    - > "Black-Box" devices – require no external field or reference (ideally).
      - – But the do respond also to gravity (more later)
    - > Where does inertia come from (Mach's Principle, Higgs field, etc.)?
  - Sensors include accelerometers, gyroscopes, tilt switches & sensors.
- Note that multiple measurements from a location sensing technology can also be used to infer "inertial" measurements (e.g., obtain time derivatives of position)
  - Magnetic, acoustic, radiolocation, GPS, etc.
  - But this is generally backwards from what people want to do
    - > Plus measurements can be noisy (more later)

Inertial Sensors: Accelerometers

- One of the two main inertial sensors, accelerometers measure the translational acceleration exerted on a body relative to some reference frame
- Key uses:
  - Airbag triggers & antilock brakes
  - Simple biomedical sensing (Fitbit)
  - Human computer interfaces - tilt (phones, joysticks Wii)
  - Low power wakeup on motion
  - Borehole and missle/aircraft/spacecraft navigation (high end!)

Inertial Sensors: Gyroscopes

- The other main inertial sensor, gyroscopes measure the rotational rate of a body about a fixed axis
- Key uses:
  - Video camera stabilization
  - Automotive roll-over detection
  - Human-computer interfaces (incl. gaming)
  - Head/body tracking
  - Augmented/virtual reality tracking
  - Again, navigation (once more, high end)

Inertial Sensors: Miscellaneous

- There are number of other sensors which could fit under the greater rubric of "inertial" sensors. Two key ones are:
  - Tilt switches for translational acceleration
    - Used for very low frequency, low resolution systems, we will comment on a few later on
  - Compasses (magnetometers) for rotational position
    - Useful for navigation in areas of *consistent* magnetic field.
    - Not inertial – exploit an outside magnetic field.
    - Covered in the last lecture.
    - Used with inertial systems in MARGs (i.e., '9-axis' IMU)

Why measure inertial parameters? Infrastructure free

- Simplifies task
  - Only body of interest is instrumented
- Vastly increases areas of use
  - Cannot provide infrastructure for the whole world
    - > Well, actually, you can (aircraft navigation, GPS)
      - – But not other worlds (yet)!
    - > …Except for indoors.
- Self-contained
  - Cannot be jammed or fooled
    - > Unless you have a huge mass laying around!

Why measure inertial parameters? The problem with derivates (1)

- There are also two key mathematical problems
  - Time lag
    - The more accurate your derivative (ie, the more points back in time you look), the greater the delay.
    - Now consider that acceleration is the **second** derivative
  - Frequency noise
    - A pure differentiator provides a linearly increasing gain with frequency. This amplifies high-frequency noise which can swamp out the signal.
    - Often have to low-pass before and/or after high-passing (see above).

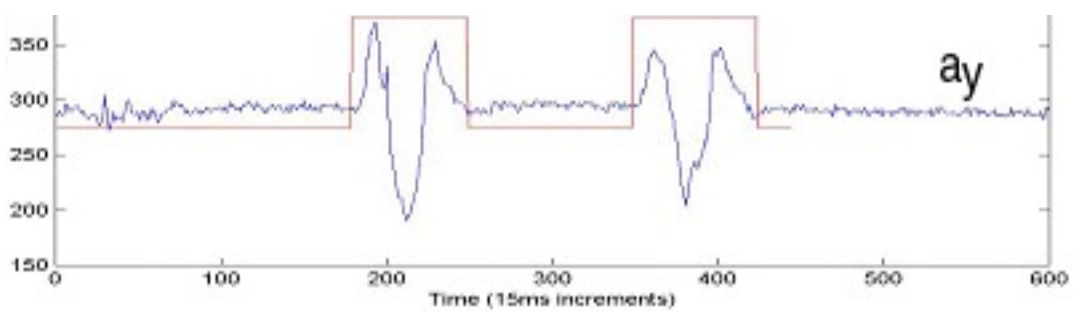
Why measure inertial parameters? The problem with derivates (2)

- It is certainly possible to derive acceleration, velocity, rotational rate, tilt, etc. from conventional positioning system
  - Both from large scale systems such as GPS and small scale systems such as the Flock of Birds
- The design problem with this is that you are measuring one quantity and then processing it to calculate another quantity, which could have been measured directly in the first place.

Note that if you're wanting to measure location in the first place, this argument is of limited value…

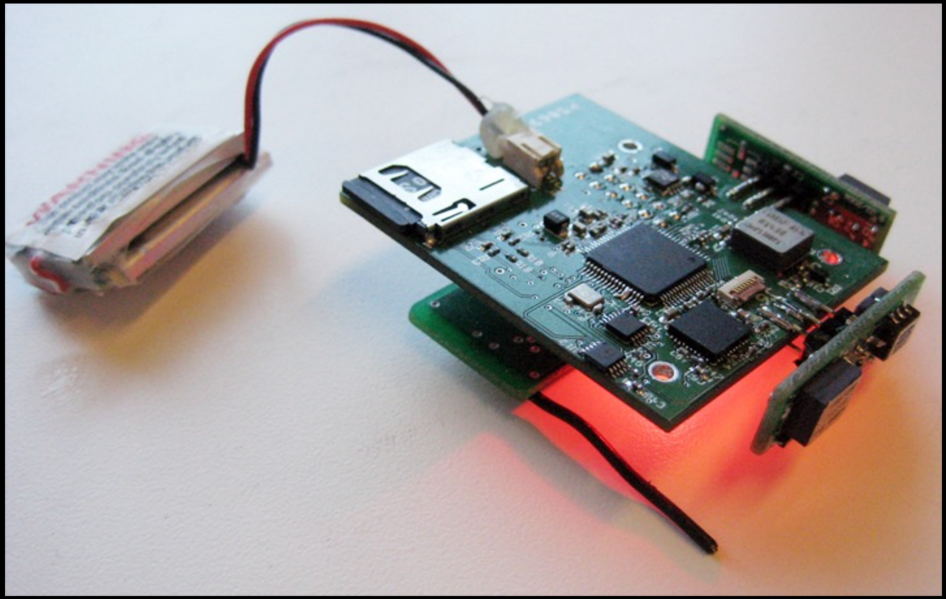
Why measure inertial parameters? More direct measurement

- Most importantly, inertial parameters are often the ones of fundamental interest.
  - Simple example with airbag
    - I don't care where the car is, just if it stopped suddenly
  - More complex example with human muscle motion
    - Unconstrained motion minimizes jerk
    - Acceleration signal provides motion parameters trivially



An Inertial Measurement Framework for Gesture Recognition and Applications Ari Y. Benbasat and Joseph A. Paradiso. In Ipke Wachsmuth, Timo Sowa (Eds.), "Gesture and Sign Language in Human-Computer Interaction," International Gesture Workshop, GW 2001, London, UK, 2001 Proceedings, Springer-Verlag, Berlin, 2002, pp. 9-20.

Return to Spring Training, 3/09



New device has onboard removable flash for continual data storage (RF synch), Bi-range full IMU

Network In Action

MIT Media Lab

mapping the

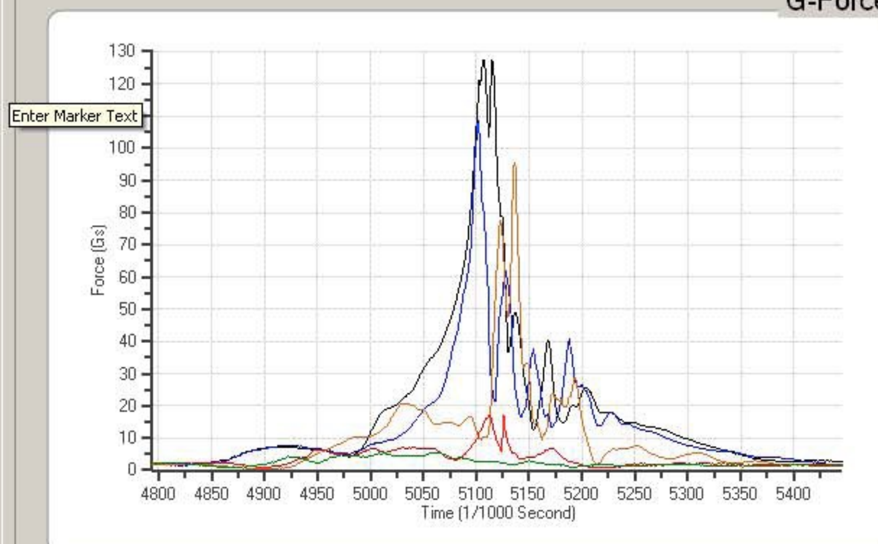
Pitcher Session Stat Sheet

Pitcher:

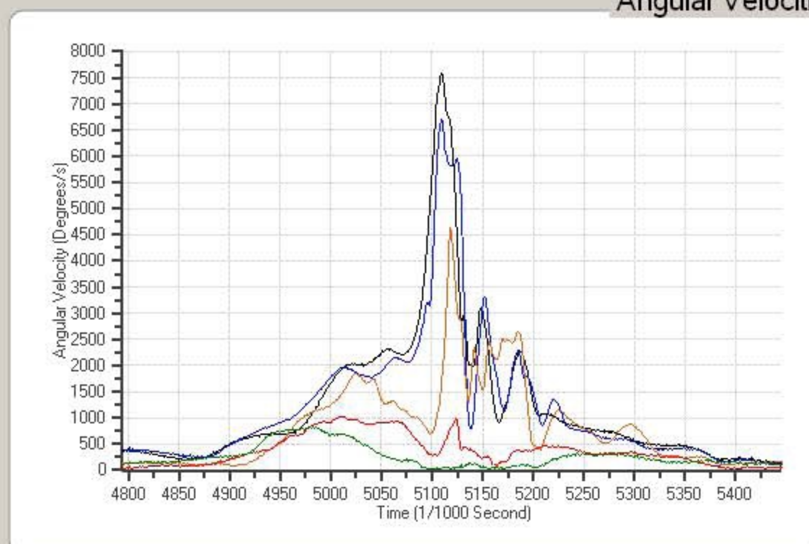
Print

	Angular Velocity: Hand Max/Stdev (degrees/sec)	Forearm Max/Stdev (degrees/sec)	Upper Arm Max/Stdev (degrees/sec)	Chest Max/Stdev (degrees/sec)	Waist Max/Stdev (degrees/sec)	G's: Hand (meters/sec²)	Forearm Max/Stdev (meters/sec²)	Upper Arm Max/Stdev (meters/sec²)	Chest Max/Stdev (meters/sec²)	Waist Max/Stdev (meters/sec²)	Count	Speed/Stdev
All Pitches	7,873.0±321.0	7,005.0±352.0	5,091.0±400.0	1,511.0±170.0	878.0±25.0	140.0±8.0	118.0±9.2	128.0±16.1	25.0±3.7	6.0±0.5	18	82.2±3.8
All Fastballs	7,611.0±306.0	7,005.0±314.0	5,091.0±408.0	1,511.0±184.0	878.0±24.0	140.0±7.2	118.0±8.9	128.0±14.7	19.0±2.7	6.0±0.5	15	82.2±3.8
Fastballs	7,611.0±306.0	7,005.0±314.0	5,091.0±408.0	1,511.0±184.0	878.0±24.0	140.0±7.2	118.0±8.9	128.0±14.7	19.0±2.7	6.0±0.5	15	82.2±3.8
2 Seam Fastballs											0	0.0±0.0
4 Seam Fastballs											0	0.0±0.0
All Breaking Balls	7,422.0±0.0	6,285.0±0.0	4,387.0±0.0	1,191.0±0.0	812.0±0.0	124.0±0.0	88.0±0.0	75.0±0.0	25.0±0.0	5.0±0.0	1	83.0±0.0
Breaking Balls											0	0.0±0.0
Curveballs											0	0.0±0.0
Sliders	7,422.0±0.0	6,285.0±0.0	4,387.0±0.0	1,191.0±0.0	812.0±0.0	124.0±0.0	88.0±0.0	75.0±0.0	25.0±0.0	5.0±0.0	1	83.0±0.0
Changeups	7,873.0±217.0	6,009.0±173.0	4,079.0±136.0	1,101.0±52.0	802.0±3.0	117.0±2.8	97.0±2.1	77.0±4.9	12.0±0.7	5.0±0.0	2	82.0±7.1

G-Forces



Angular Velocities



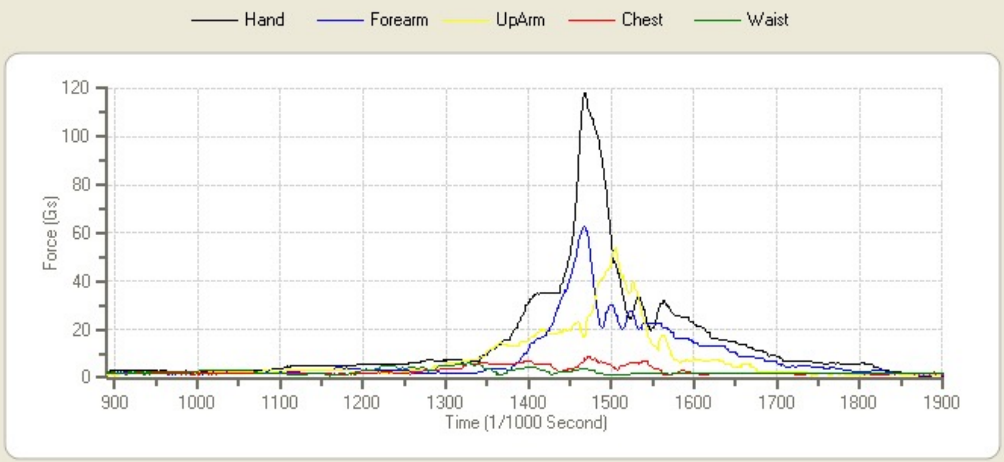
Batter: W

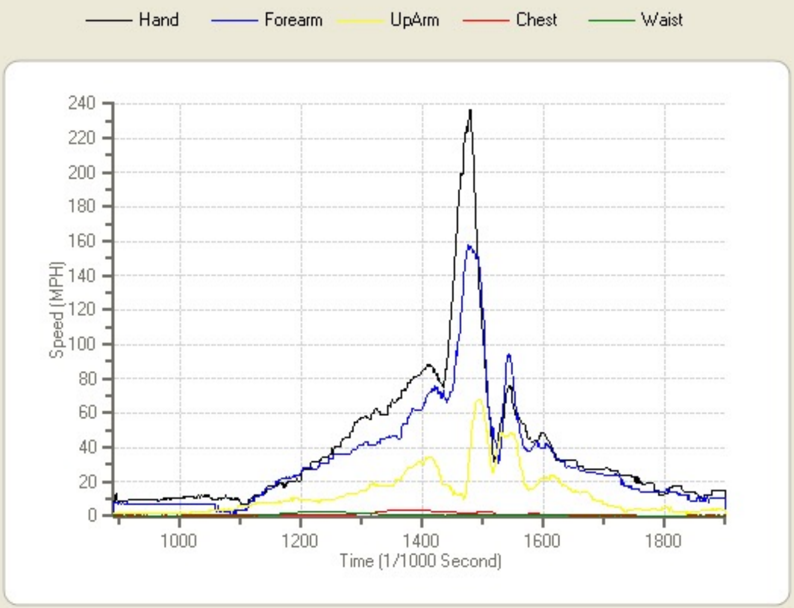
Impact Swing

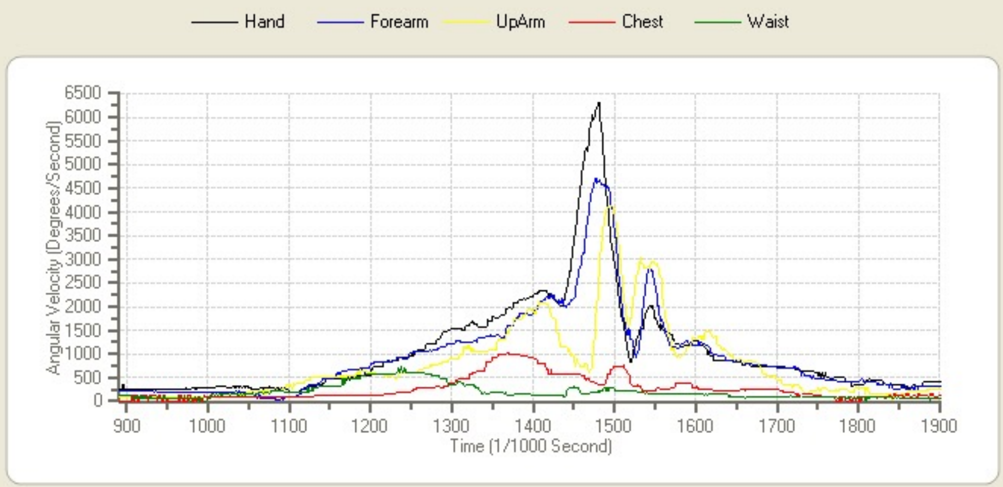
Swing ID: 436

Speeds	Predicted Peak Bat Speed	Peak Hand Speed	Peak Forearm Speed	Peak Up Arm Speed	Peak Chest Speed	Peak Waist Speed	Swing Duration	Impact Time
	-23700	237	159	68	4	3	910	-1

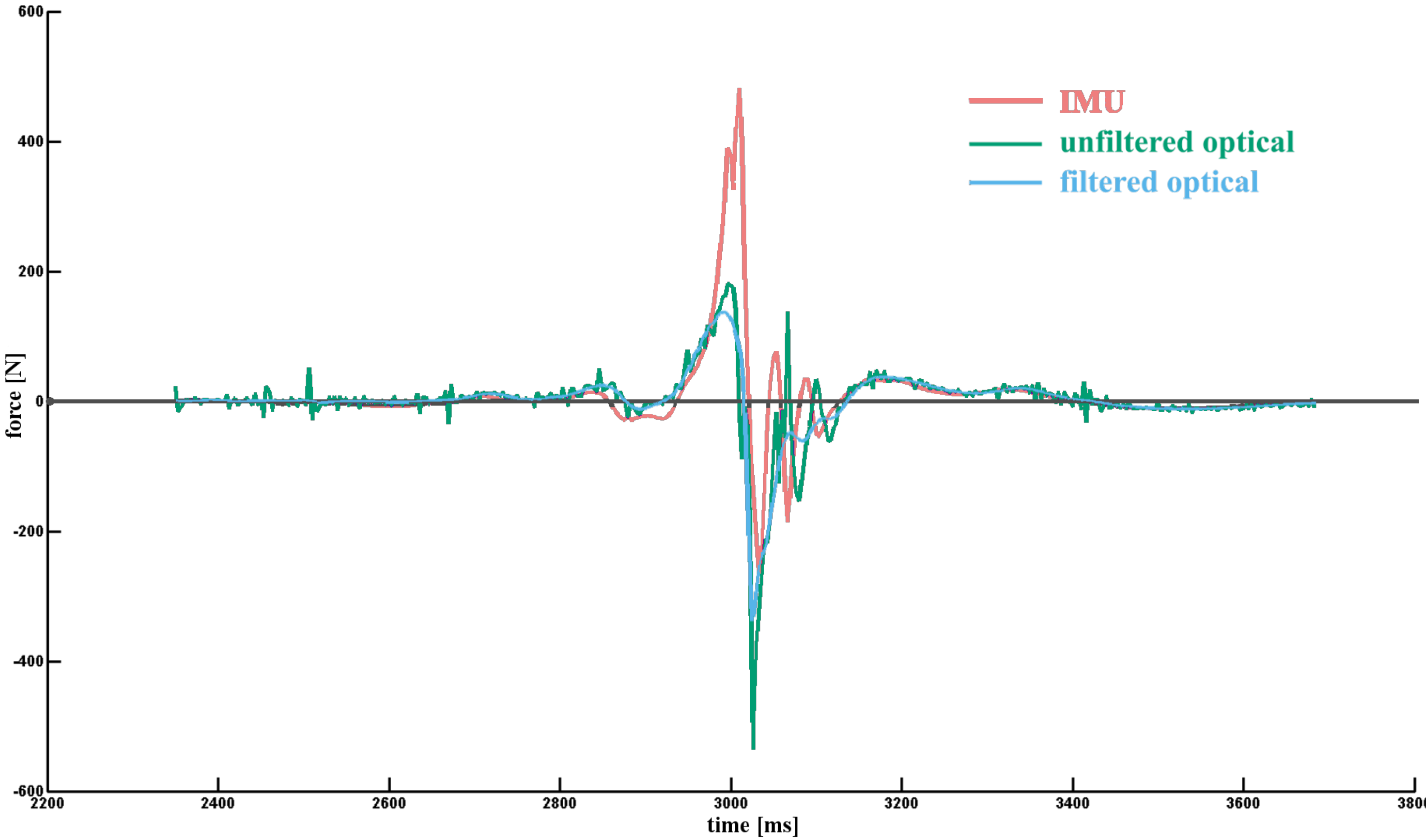
Peak Timing	Bat-Hand Delta	Hand Forearm Delta	Forearm Up Arm Delta	Up Arm Chest Delta	Chest Waist Delta	
		3	-19	119	124	







Wrist force – optical vs IMU



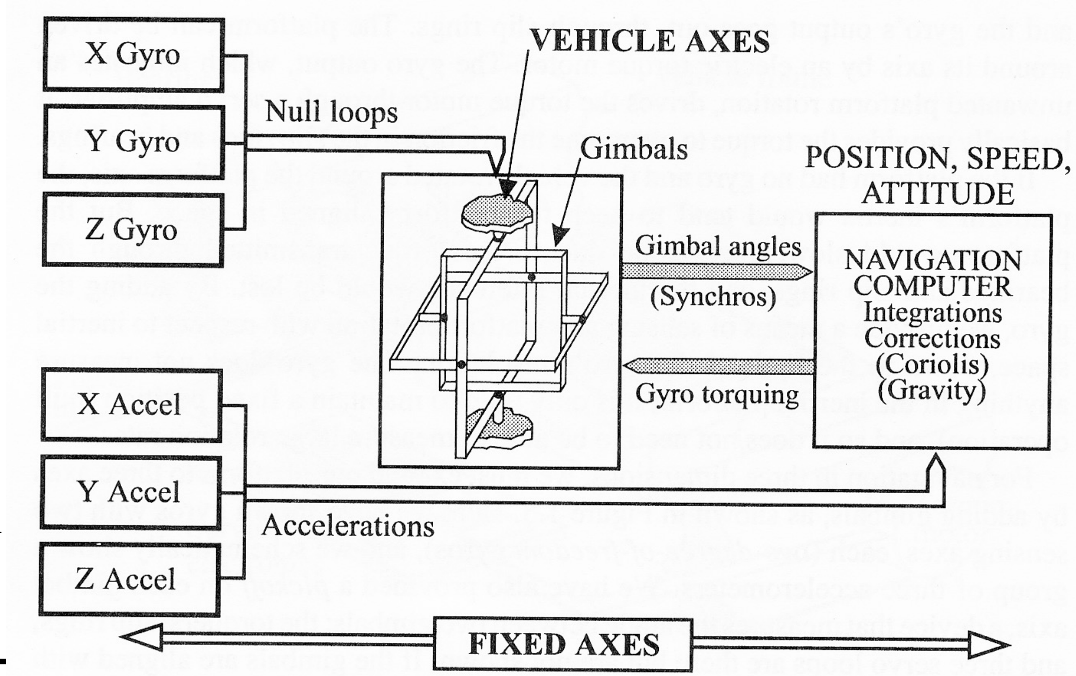
Direct inertial measurement sees higher force!

Inertial Measurement Units: Basics

- An inertial measurement unit (IMU) is a sensor package containing three orthogonal axes of rate sensors (gyros) and three orthogonal axes of acceleration sensors (accelerometers)
- Historically used for inertial navigation or tracking – until recently, out of price range for HCI
- Made by:
  - Intersense (now Thales) http://www.isense.com
  - Crossbow http://www.xbow.com
  - Many Others…. (e.g., Sparkfun)
  - Us http://www.media.mit.edu/resenv/Stack (and Sensemble)
- Was about $1000 and under 10 cm^3 - chips now!

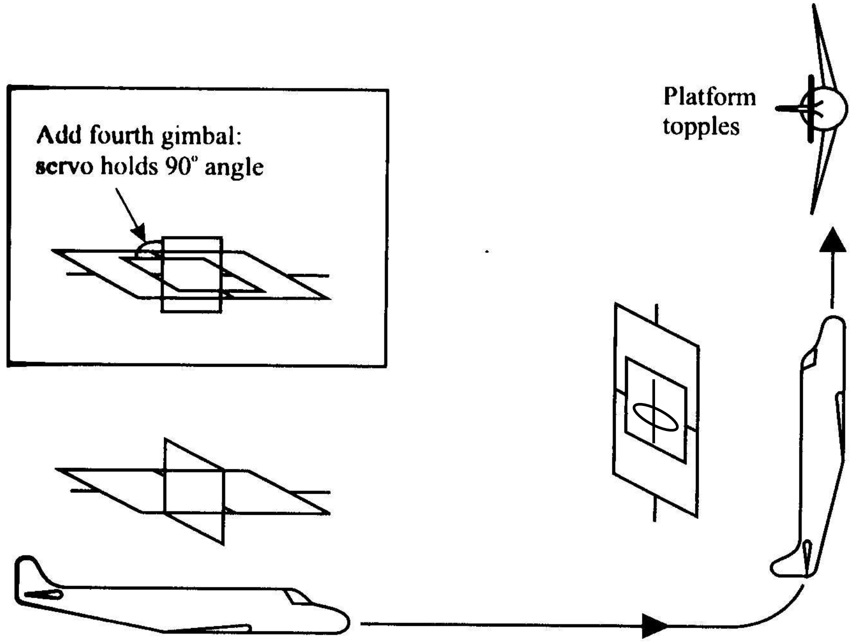
Inertial Measurement Units: Gimballed

- Most early IMUs where placed on a platform which stayed fixed relative to the inertial or earth frame
  - Still used for very accurate systems
- Allows for gyros to measure a much smaller range, since they only detect the small deviations (more linear, more acurate)
  - Simplifies xforms
  - Platform is servoed
    - Zero rate
- However
  - Very expensive
  - Suffer from gimbal lock



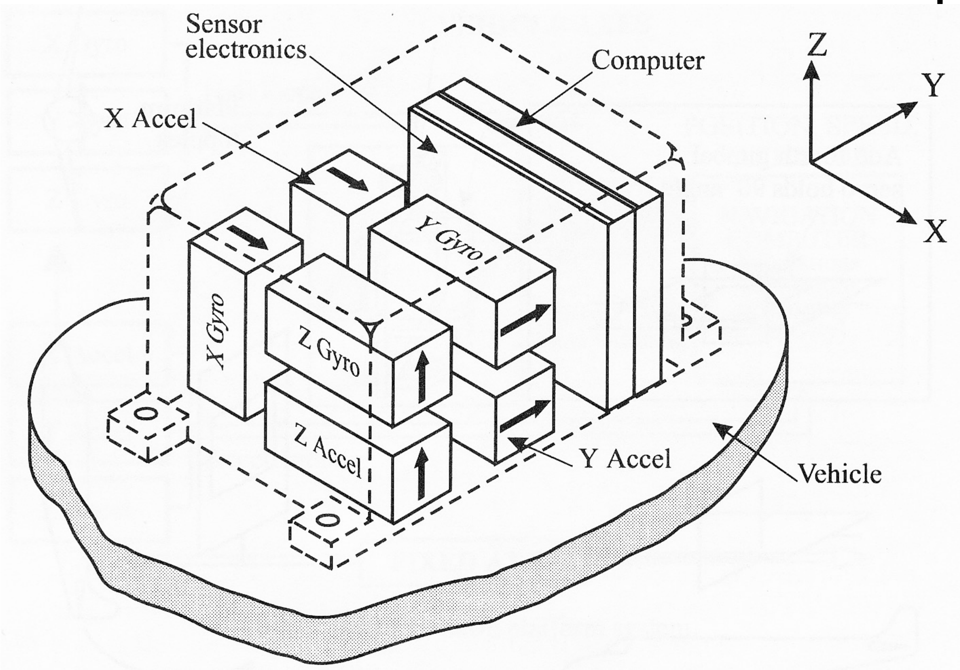
Inertial Measurement Units: Gimbal Lock

- Given a fixed set of movements, it is possible to align all three axes on the gimballed platform, causing it to lock up and "topple"
- Can be fixed by adding a fourth gimbal (expensive)



Inertial Measurement Units: Strapdown

- Far easier than gimballing, we can simply fix the IMU in the frame of the device.
- Mechanically much simpler and stronger, but increases the complexity of the math if world frame position/orientation is needed
- Most useful if body frame itself has meaning
  - Makes choice of alignment key
- Virtually all IMUs for HCI are strapdown



Inertial Measurement Units: Tracking (1)

- IMUs are traditionally used for navigation or dead-reckoning.
  - Given a known starting position and orientation, data is integrated forward to get current position and orientation

Position Calculations

- $X = \int\int a_x \, d^2t$
- $\theta = \int \omega \, dt$

Lots of ways to integrate (Polynomial, Simpson's Rule, etc.)

Note that gravity complicates things – rotation measurements must compensate for the change in the gravitational vector, which needs to be subtracted from the acceleration – also note that this is done in the body frame usually should be transferred to inertial coordinates.

You need to estimate rotation in order to properly do translation if the IMU can rotate

But, there's more…..

Inertial Measurement Units: Fundamental Error Source

- Bias drift
  - Changes over time in the baseline (zero input) output of the part
- Scale factor drift
  - Changes over time in the slope of the input-output curve
- Drift results in an additive noise which causes an error proportional to t in angle and t^2 in position
- These noises/errors are separate from the additive white noise seen on all sensors
  - If this is Gaussian, position also has a random walk component with error proportional to t

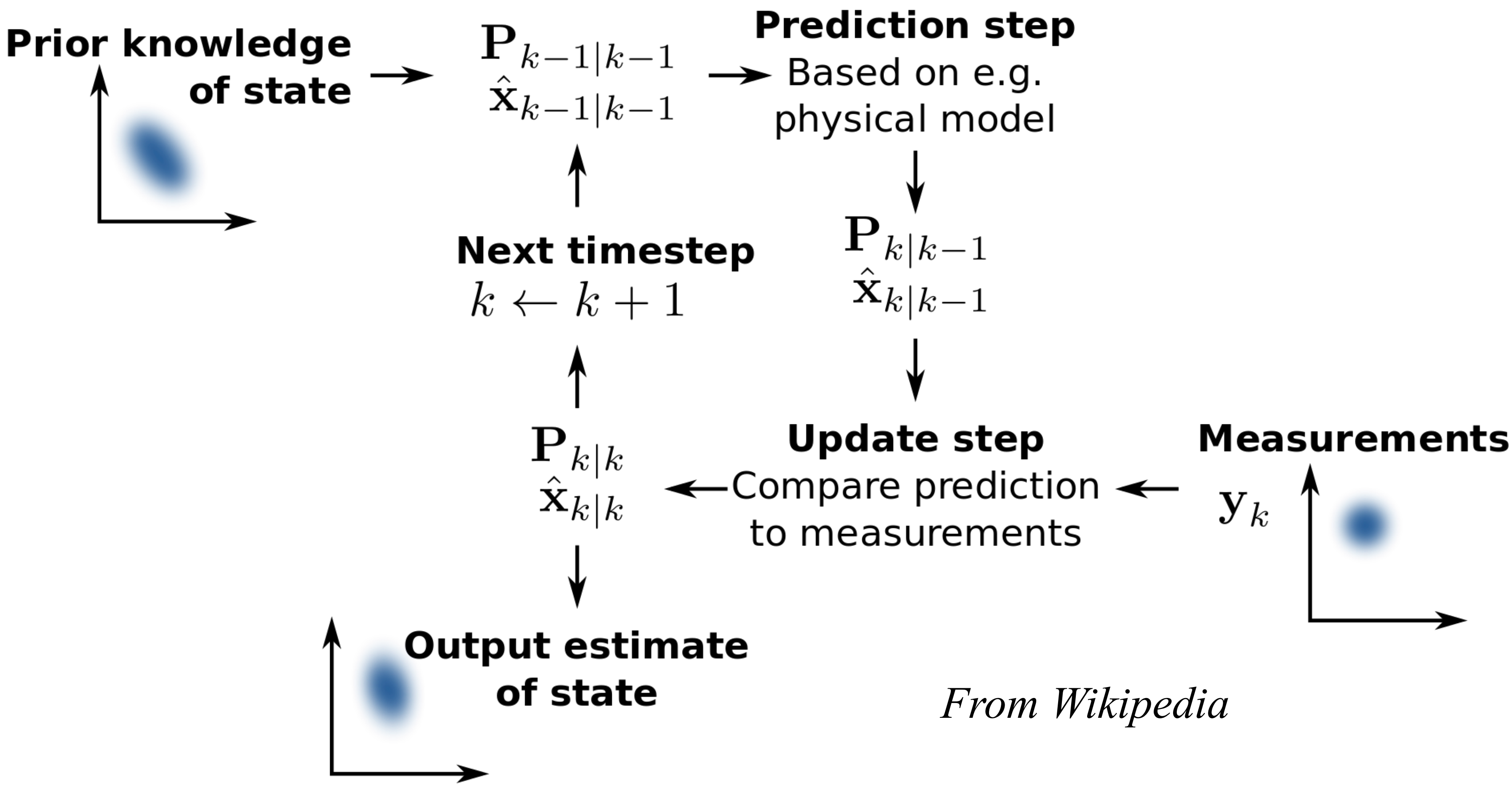
Inertial Measurement Units: Tracking (2)

- However, IMUs made from low-cost parts quickly diverge from reality because of both poor drift *and* random walk noise
- When noisy data is summed, the σ is increased by a factor of $t^{1/2}$
  - For example, in a gyro, this creates an error in the orientation estimate
  - That error then couples into the position estimate ($\Delta x = d\theta\ r$)
- The only solution is to use external information to reset the orientation or position at regular intervals

State Estimation - Kalman Filtering

- The most common algorithm for doing this is a **Kalman Filter**, which combines knowledge about the error in the measurements and the error in a model of the system propagation to give a (linearly) optimal results (minimizes mean-squared error)
- Other estimation techniques exist (e.g., particle filtering, extended Kalman filtering – nonlinear techniques), and some are embedded in IMU chips (e.g., for calculating orientation – Invensense for example)

Kalman Filtering



From Wikipedia

Relate measurements to state you want to infer. Drives errors to zero in least-squares optimal sense

Principle of Equivalence

- Acceleration (a) is the second derivate of position with respect to time ($\ddot{x}$)
- Newton's 1st Law: An object in motion remains in motion unless acted upon by outside forces
- Einstein's Principle of Equivalence: The acceleration due to gravity is indistinguishable from other accelerations.
  - Gamow vs. Draper
    - > Gravity gradient (at least for a nonconstant g)
    - > Rotate the inertial platform as the earth curves underneath
      - – Schuler Tuning (add pendulum dynamics, with the mass @ earth's core)

ACCELEROMETERS

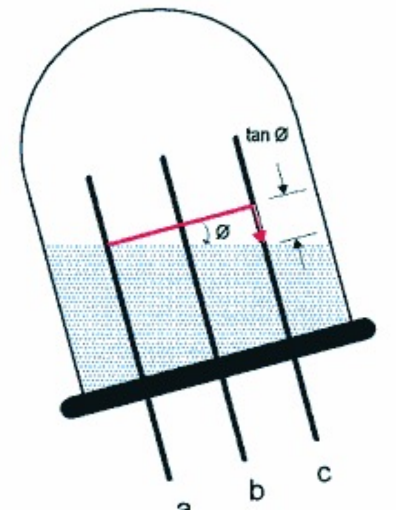
Principles of Accelerometry

- Newton's 2nd Law → F=ma
  - Since force is a fundamental quantity, we derive the acceleration by determining the force on an object of known mass (i.e the proof mass)
- This proof mass is usually attached to a spring of some style allowing us to use Hooke's Law
  - $F = -kx$
  - As $F = ma$, $a = -x(k/m)$
  - Deflection can then be converted into acceleration using knowledge of the mass and spring constant

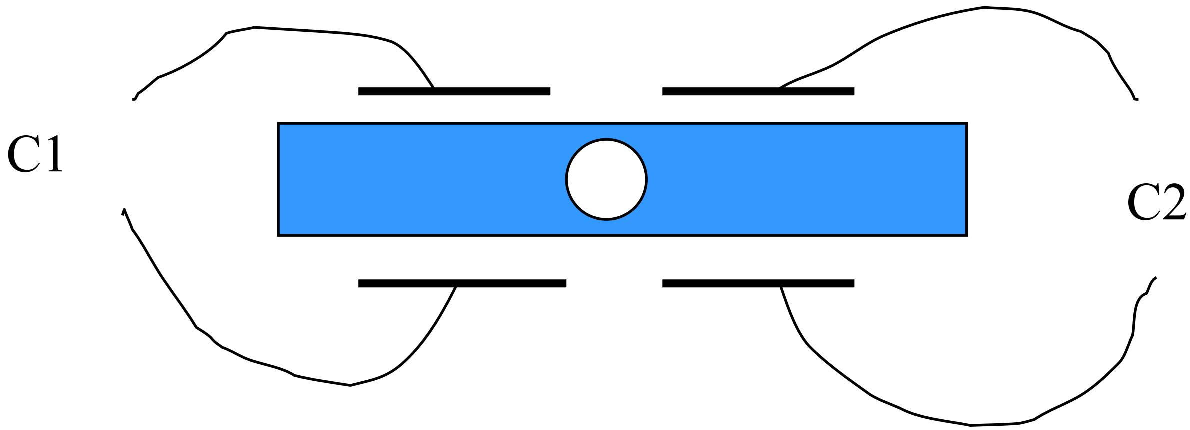
Accelerometers: Fluid Inclinometers

Check out Spectron Glass

- Not used as an accelerometer per se, but very useful for determining the tilt of a slowly moving object
- Inclinometers are most often built as a small bubble filled with electrolytic fluids.
- These devices have slow response and tend to be sloshy.
- However, in steady state, differences of 0.5^{o} or better can be detected



Inclinometers (bubble levels)



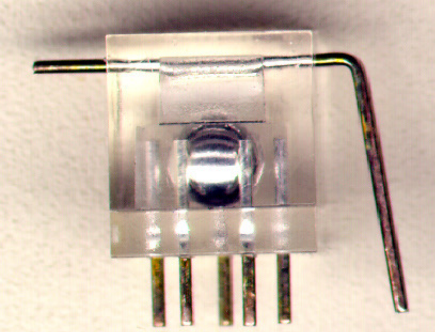
- Bubble (white) in fluid (blue) changes capacitance when it moves across plates
- (C1 – C2) / (C1 + C2) = relative bubble displacement
- Can also read bubble position optically

EL-905 ELECTRONIC BUBBLE LEVEL
(Hamar Laser, CH)

- Level is accurate to 0.5 arc seconds (0.00003"/ft or .0025 mm/M)
  - [Also available with 0.1 arc second accuracy]
- Large measuring range of +/-1000 arc seconds (0.06"/ft or 5 mm/M)

ALPS SPSF100100
SMT version of "ball in cup"

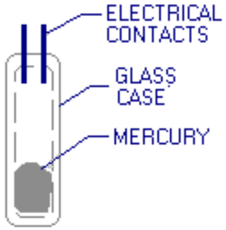
Accelerometers: Tilt Switches



3-axis "Ball in Cup"

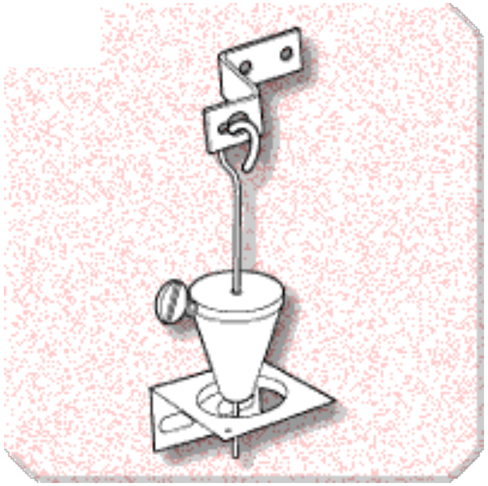
- Effectively a threshold on a single angle (with respect to gravity), tilt switch draw virtually no power and are excellent for simple motion detection

Mechanical tilt switches can also be spring-mounted for higher acceleration thresholds

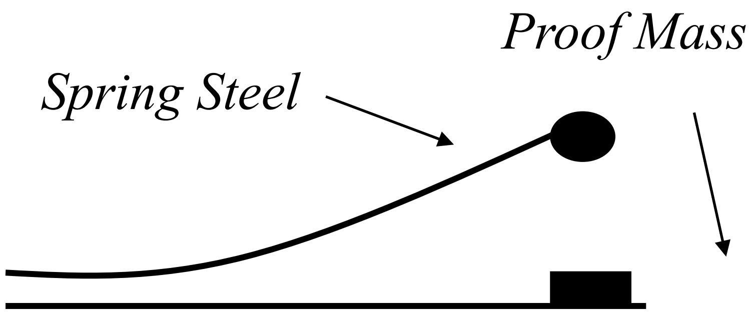


- Mercury tilt switch
  - Connection between two pins made or broken by bubble of mercury

- Pinball tilt switch
  - Cross between mercury tilt switch and inclinometer

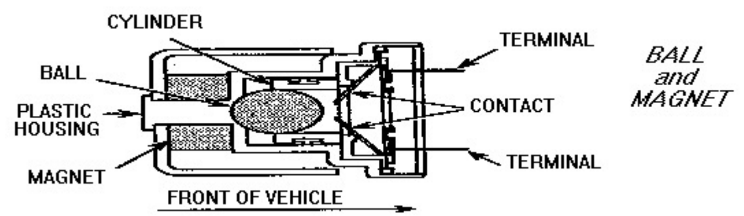


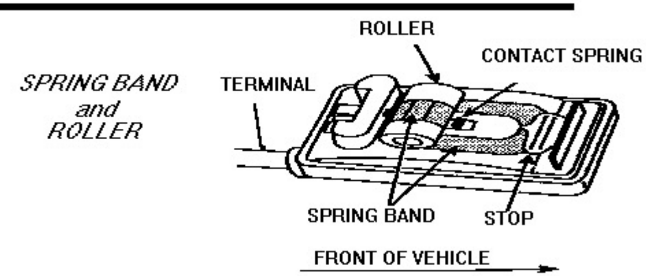
Accelerometer switches and piezo cantilevers



Proof Mass displaces under acceleration
Closes switch above threshold

- Acceleration switch
  - e.g., proof-mass reed, ball in magnetic can (old airbag sensors!)
  - Made by many companies
- Piezoelectric Cantilevers
  - Made by MSI



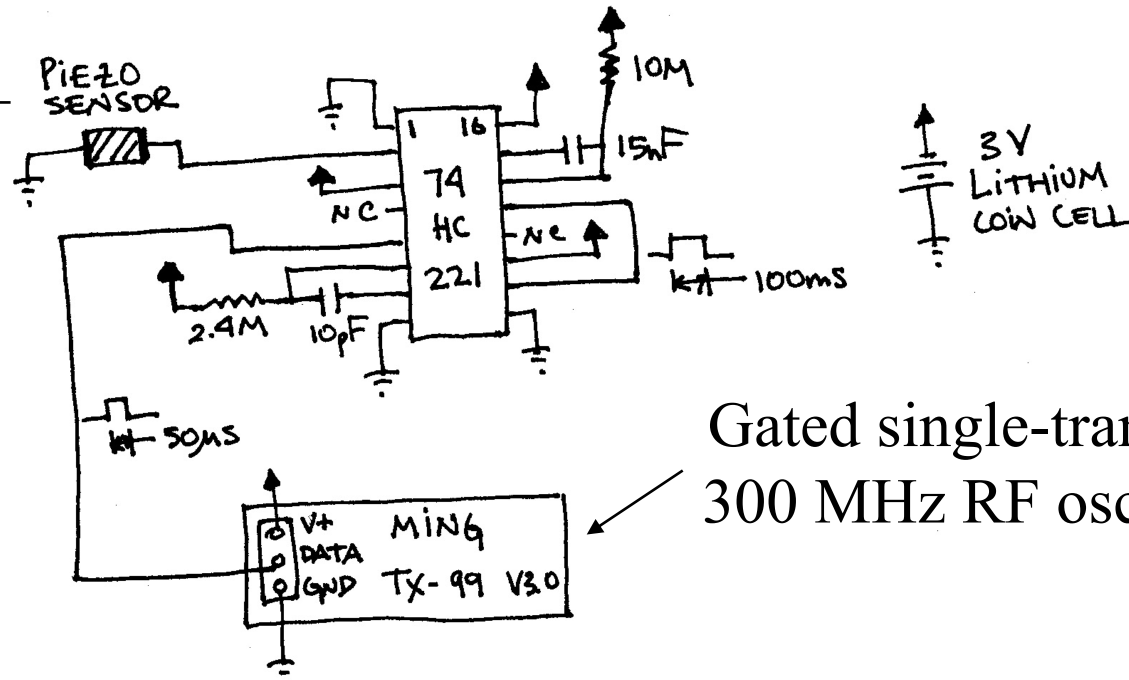


Vintage Ford Airbag Sensor

Giveaway Sensor Schematic

MSI Minisense 100

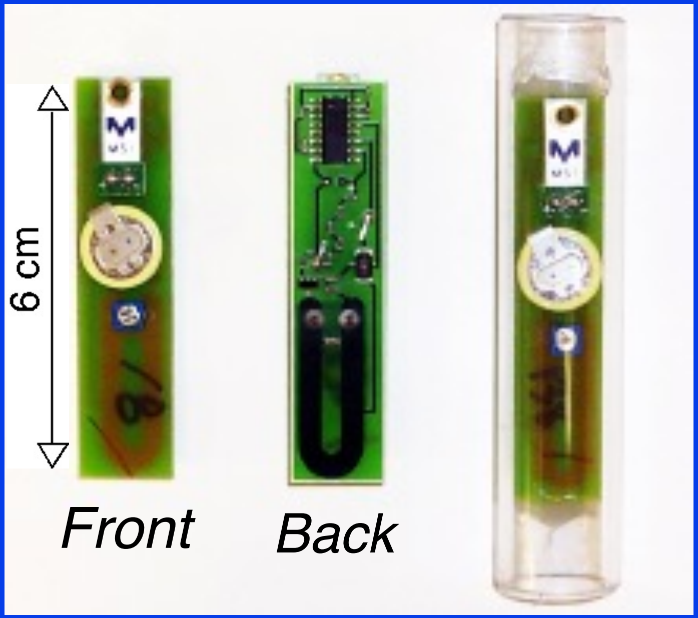
Could be mechanical tamper switch



Gated single-transistor 300 MHz RF oscillator

- 100 ms dead timer prevents multipulsing
- Ultra low power – battery lasts up to shelf life
- Extremely cheap – e.g., under $1.00 in large quantity

The Wireless Jerk Sensors



- Very simple motion sensor
  - Cantilevered PVDF piezo strip with proof mass
  - Activates CMOS dual monostable when jerked
  - Sends brief (50 μs) pulse of 300 MHz RF
  - Glued into a tube for simple handheld use

Demos

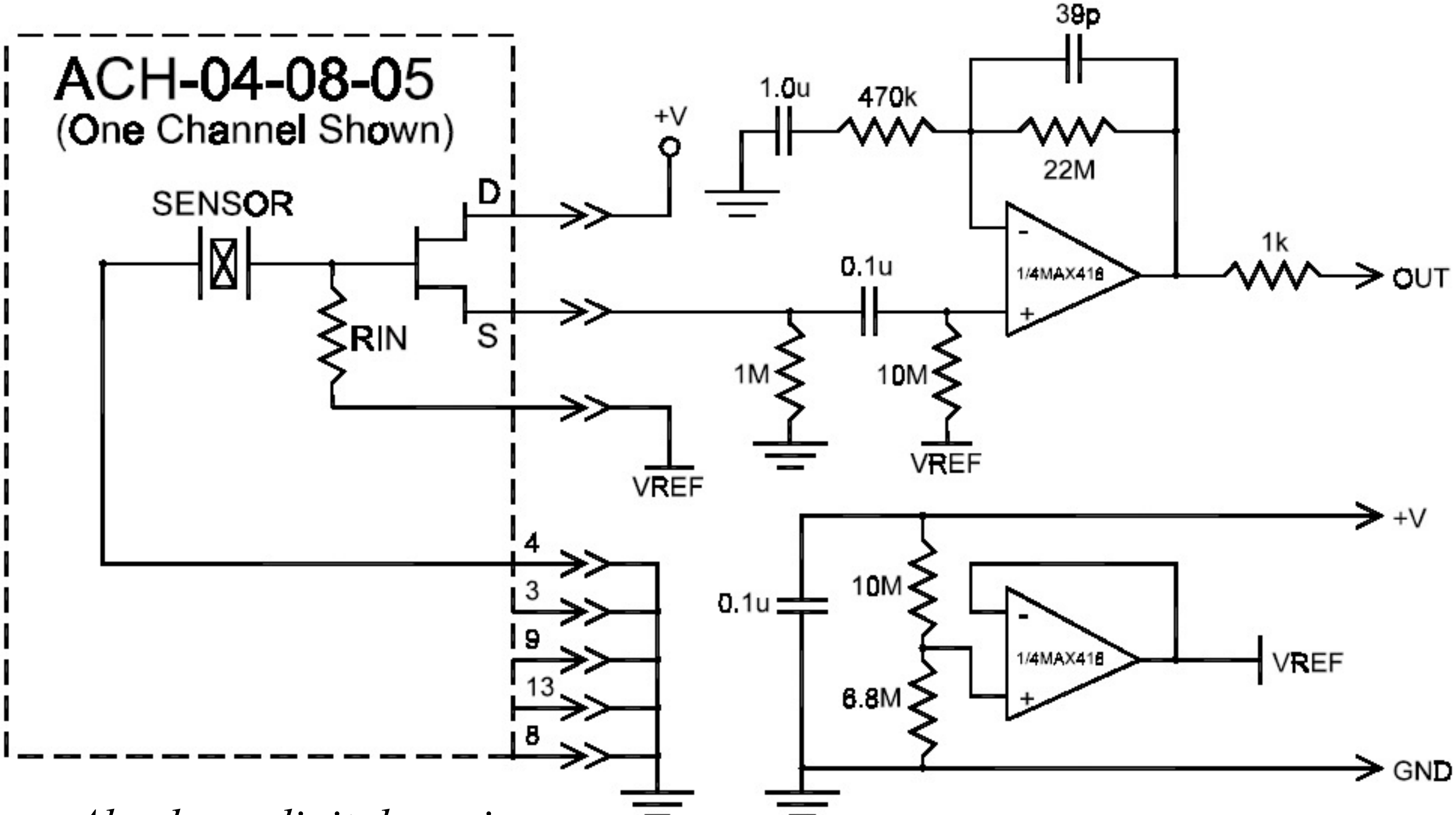
Early "conductor" mapping in Lab

Accelerometers: Piezoelectric

- Piezoelectric accelerometers use a cantilevered beam as a combination proof mass and spring
- Beam is deflected by acceleration, creating a charge related to its mass and flexibility
- This charge can be measured to find the acceleration.
- ACH-04-08 from MSI (3 axis)
  - Range: ±10g to ±250g
  - Size: 0.3in x 0.3in x 0.2in
  - Bandwidth: 5 kHz
  - Noise: 250mg
  - Cost: $25

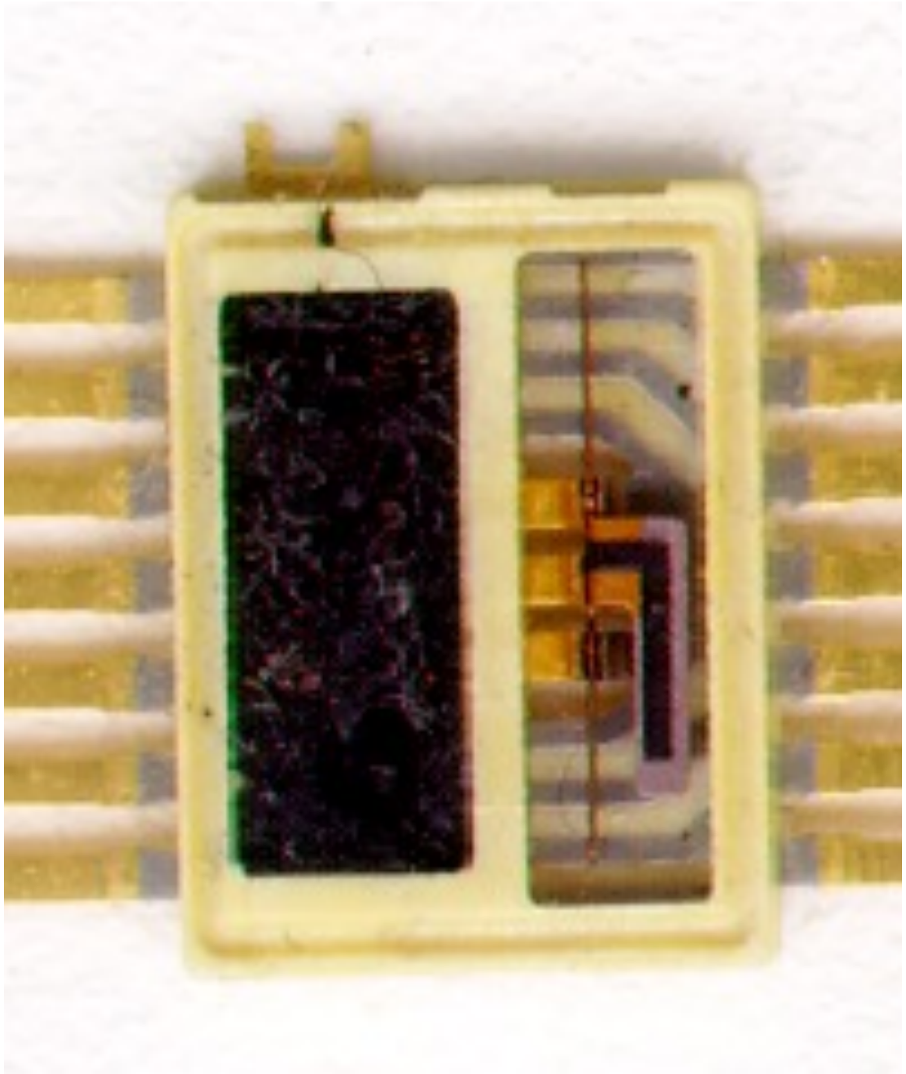
Accelerometers: Piezoelectric - Circuitry

Analog Test PCB: Low Power, Single Supply Circuit

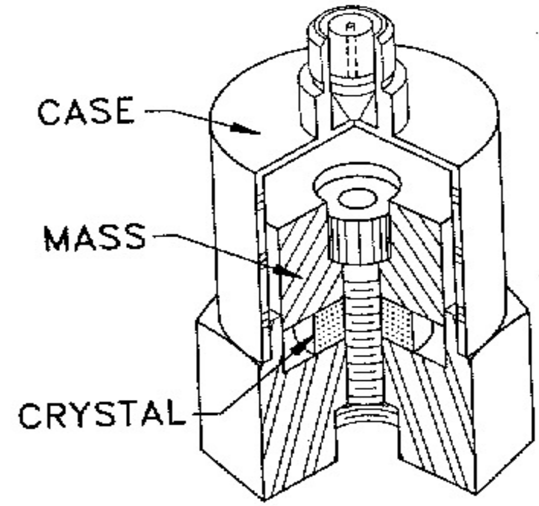


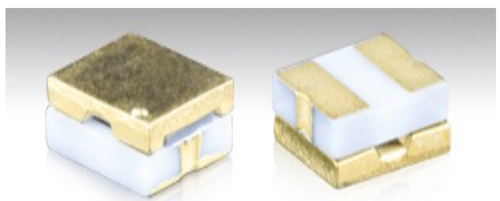
Also have digital versions

What's inside… (complex folded beam)



Piezoelectric accelerometers for rugged, sensitive vibration measurement





Endevco PicoChip

- Lamerholm, Endevco, Etc.

Miniature Piezoceramic Accelerometers

Piezoelectric Ceramic Sensors (PIEZOTITE®)

muRata

Shock Sensors

The shock sensor, PKGS series, is acceleration sensor with 2 terminals and detects acceleration & shock to be applied from outside, as electrical signal.
By bimorph piezo elements clamped at the two-end with original polarization technology, the shock sensor has high sensitivity and excellent durability.
The shock sensor is reflow solderable SMD type.
The shock sensor can have inclined primary axis so that appropriate shock sensor can be chosen for shock detection in HDD (Hard Disk Drive) and optical pick-up control in optical drive & optical-magnetic Drive.

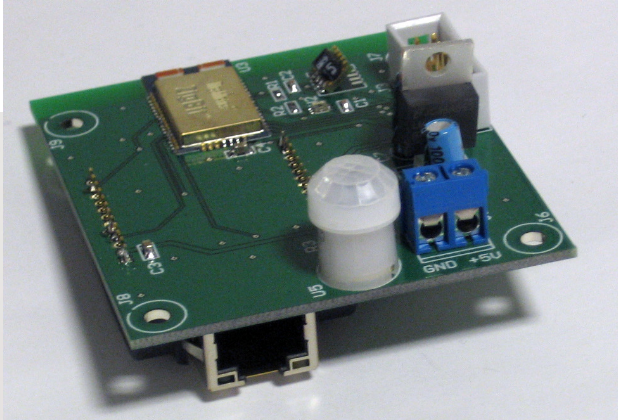
■ Features

1. Small size, low profile, high sensitivity and excellent durability.
2. Excellent linearity.
3. High resonance frequency and wide bandwidth.
4. Available tape and reel packaging.
5. Reflowable.
6. In addition to the voltage sensitivity type shock sensor (ME, LB and LC series), new type, the electrical charge sensitivity type shock sensor (NB, MF and LD series) are released. NB, MF and LD series have better anti-reflow temperature.

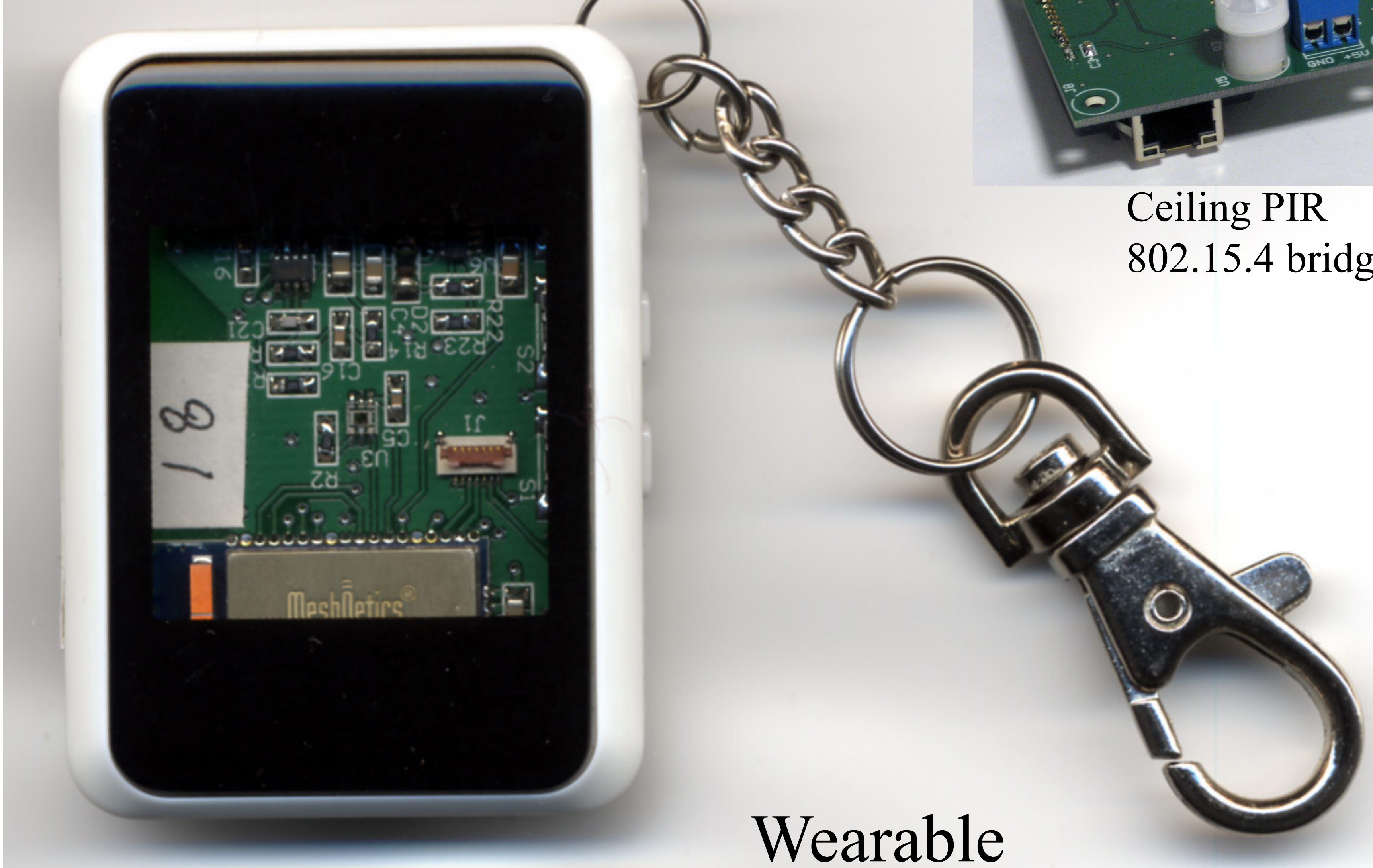
■ Applications

1. HDD data writing protection, while shock is applied from outside.
2. Shock detection and protection in DVD, CD-R, CD-RW etc.
3. Pick-up control for disk type storage in Digital camera, Camcorder etc.
4. Other applications requiring acceleration detection.

Wireless Monitor



Ceiling PIR
802.15.4 bridge



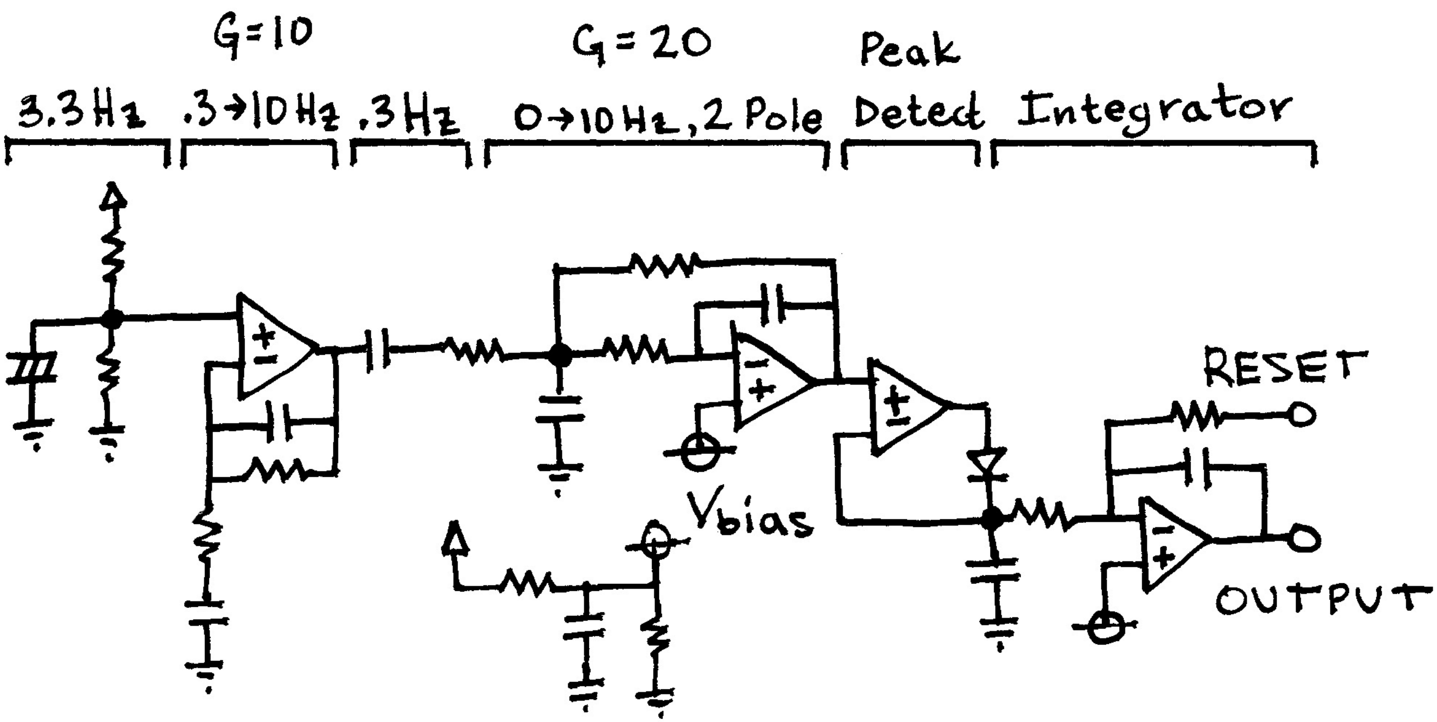
Wearable

Integrated vibration, T & H, Light @ μW

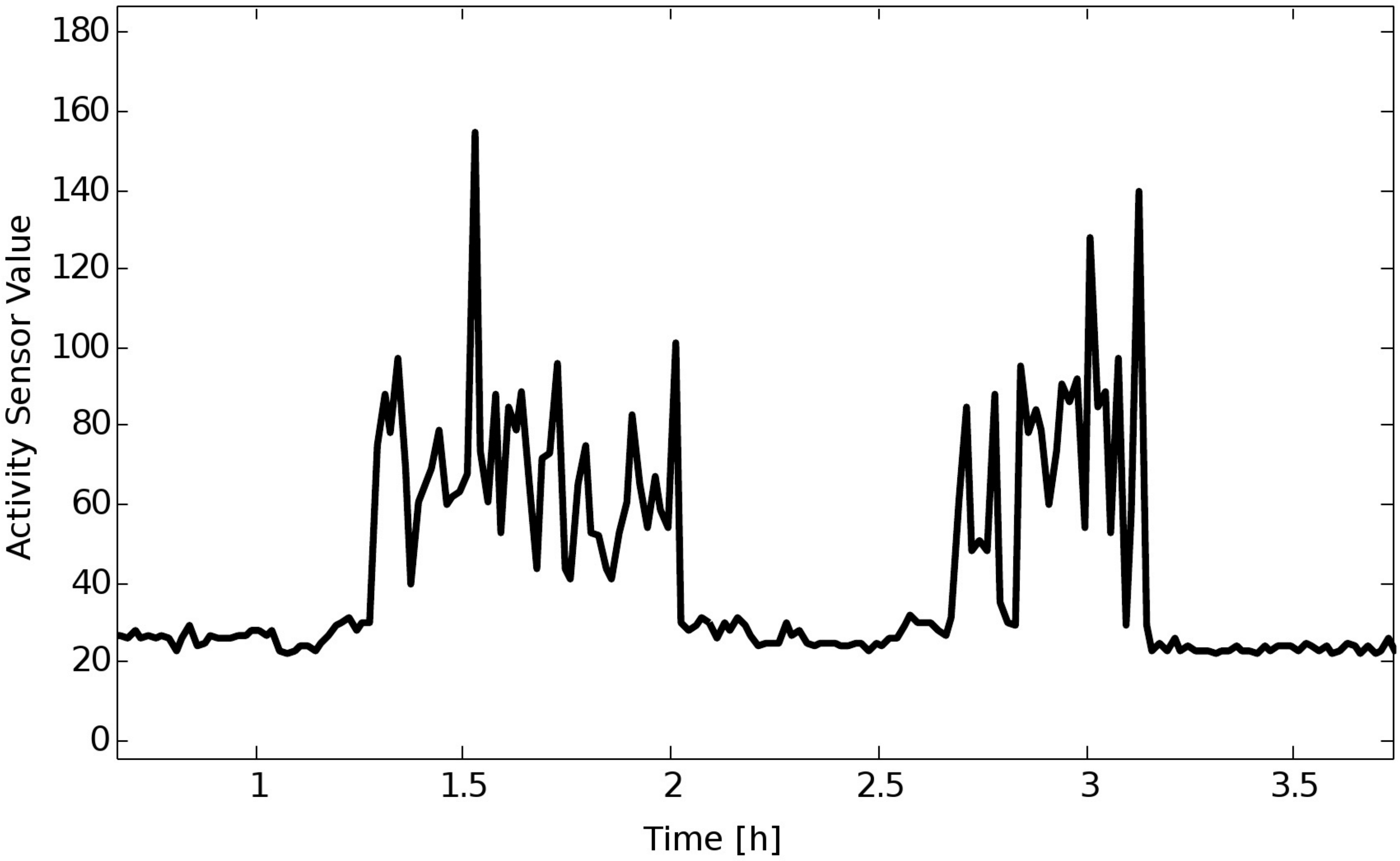
Mark Feldmeier

LOW POWER ACTIVITY SENSOR

Passive, surface mount, piezo element (1:2:4 - x:y:z sensitivity)
.1Hz to 10Hz frequency range
Micro-power op-amps with low cross-over distortion
1 minute integration time with reset



LOW POWER ACTIVITY SENSOR

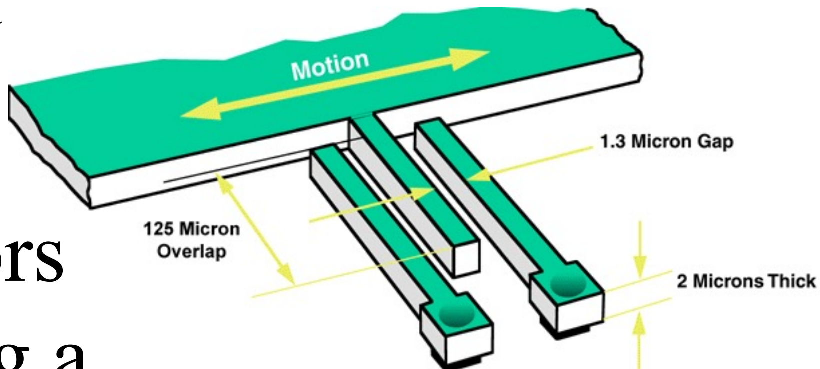


Sidebar: What are MEMS?

- Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate.
- This combination not only reduces costs, but the close integration of sensor and signal processing greatly reduces system noise
- MEMS have been used for everything for sensors to microgenerators.
- Many companies make MEMS accelerometers now
  - Analog Devices, Motorola, Silicon Designs…
  - ST Microelectronics makes a 3-axis device!

Accelerometers: MEMS

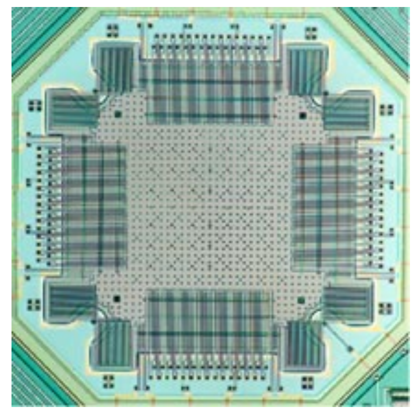
- Most MEMS accelerometers are based on interdigitated capacitors, as shown at right.
- Proof mass servoed

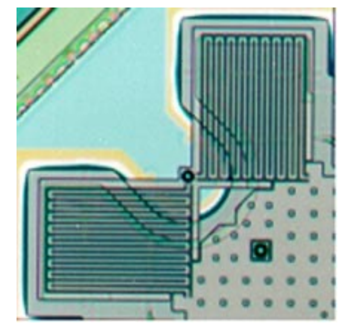


- Motion unbalances the pair of capacitors shown, unbalancing a driven signal.
- The most common MEMS accelerometer was the ADXL202(3) from Analog Devices, and was a staple of low cost inertial sensing.

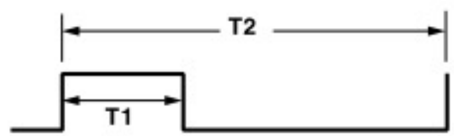
Accelerometers: ADXL202

- ADXL202 from Analog Devices (2 axis)
  - Range: ±2g
  - Size: 5mm x 5 mm x 2 mm
  - Bandwidth: 5 kHz
  - Noise: 4.3mg (@50Hz)
  - Cost: $10



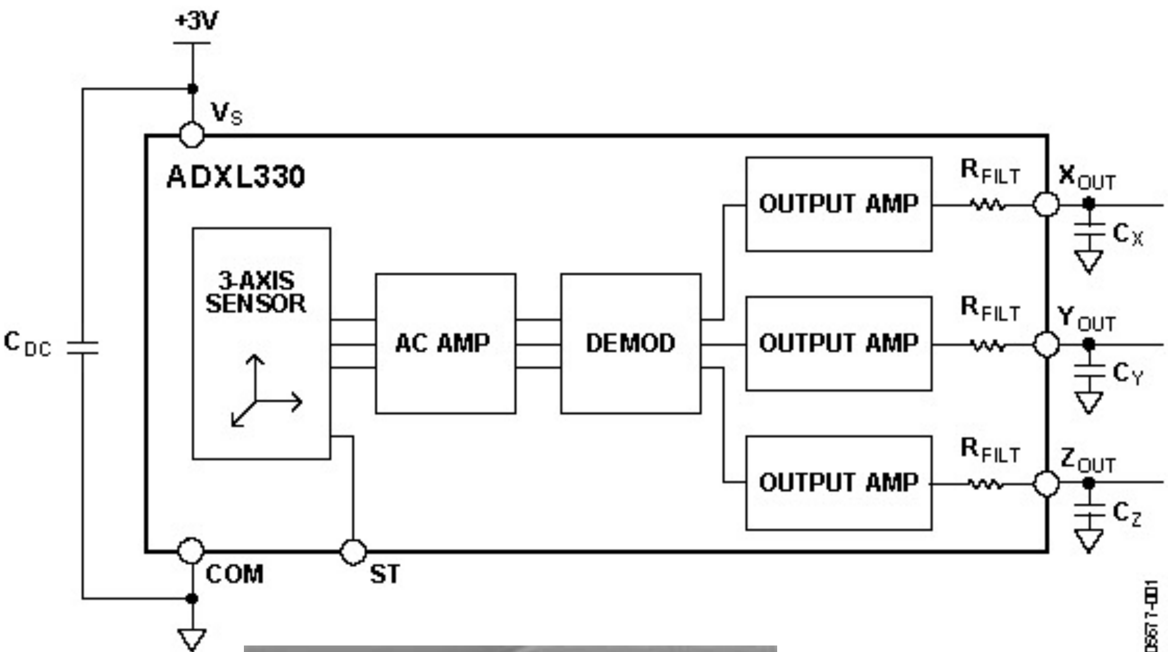


- Duty-cycle output for easy interfacing



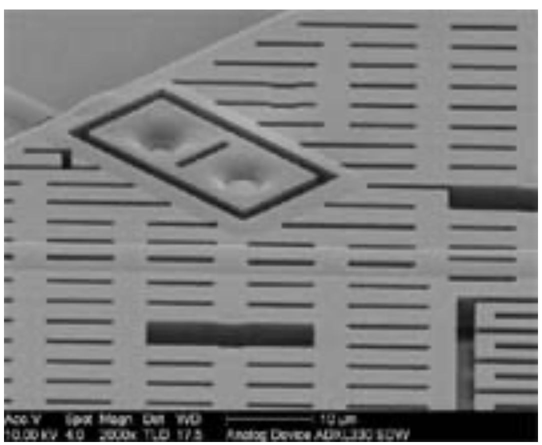
$A(g) = (T1/T2 - 0.5)/12.5\%$
$0g = 50\%$ DUTY CYCLE
$T2 = R_{SET}/125M\Omega$

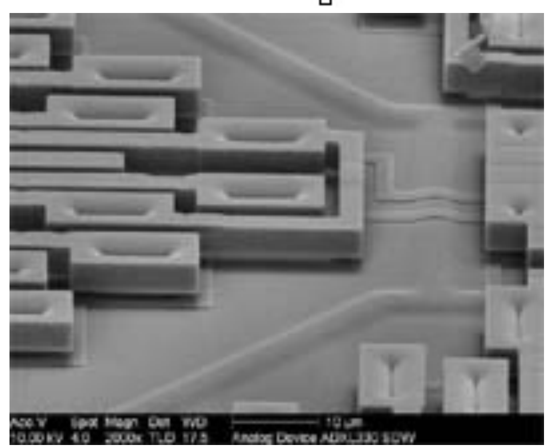
ADXL330 - 3-axis accelerometer



Specifications	
TypicalBand Width (kHz)	1.6kHz
Voltage Supply (V)	2.0 to 3.6
Range	+/- 3.6g
Sensitivity	300 mV/g
# of Axes	3
Sensitivity Accuracy (%)	Â±10
Package	4mm x 4mm LFCSP
Supply Current	0.2mA
Noise Density (Âµg/rtHz)	280

Find Similar Products

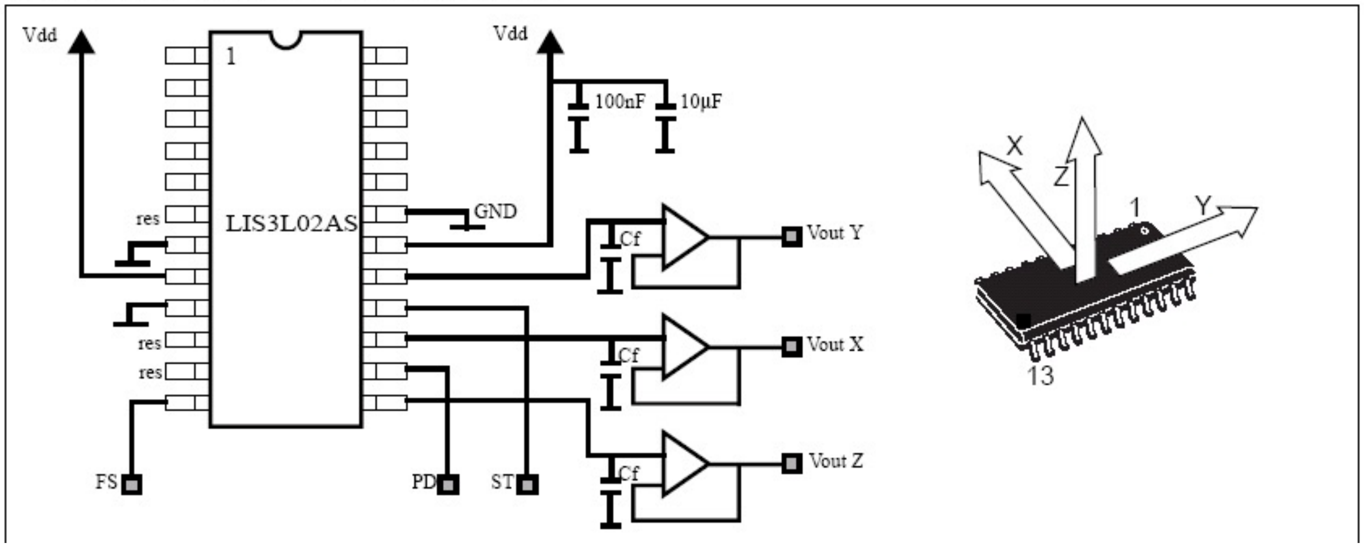




Single proof mass for all 3 axes

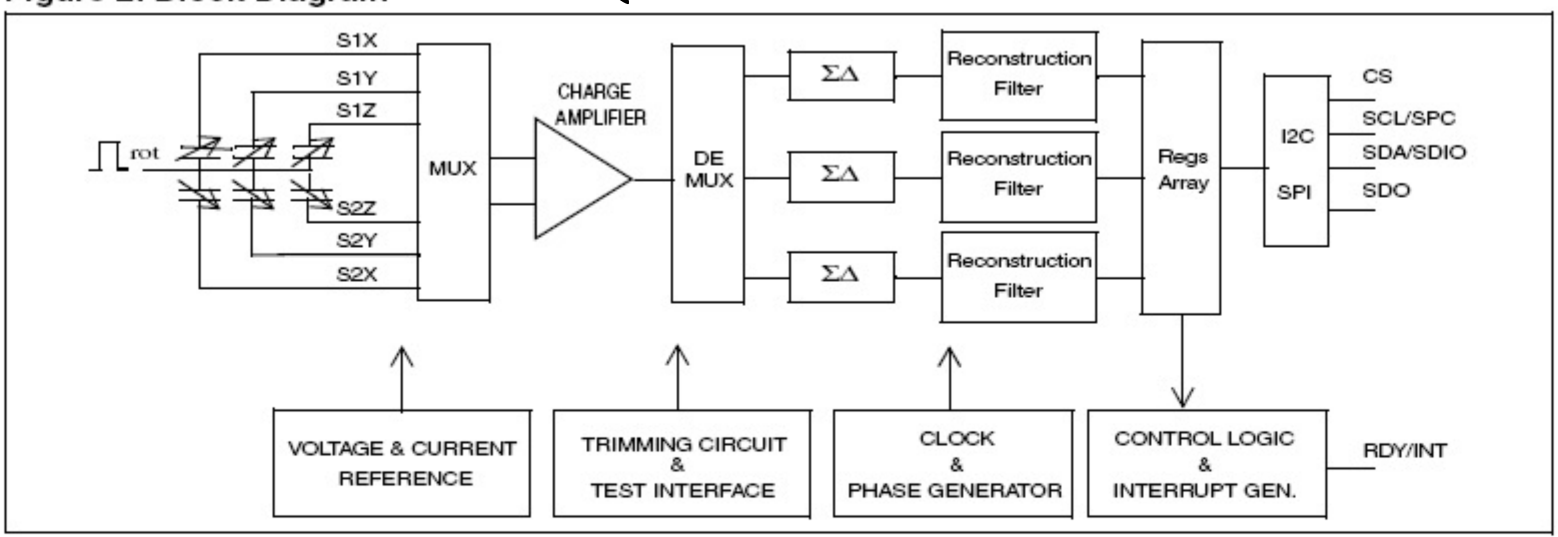
ST single-chip 3-axis accelerometers

Figure 1 LIS3L02AS ELECTRICAL CONNECTION



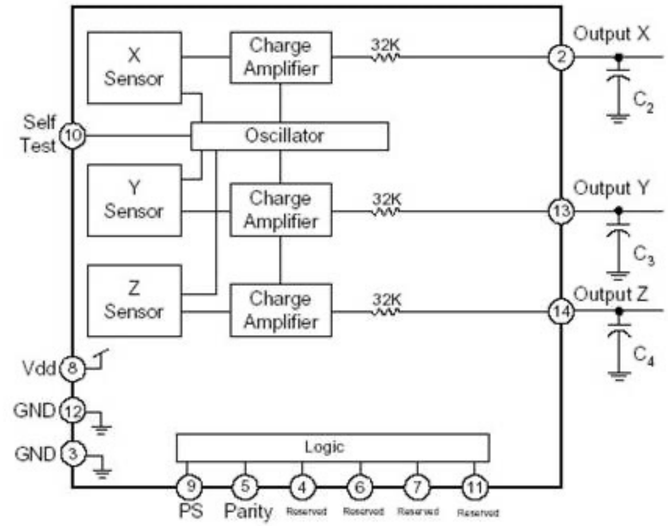
Analog Outs

Figure 2. Block Diagram LIS3L02DQ



Digital Output

3-Axis accelerometers from others…



Kionix KXM52

FREESCALE MMA7260Q XYZ-AXIS LOW g ACCELERATION SENSOR

Device	Acceleration (g)	Sensitivity (mV/g)	Sensing Axis	Frequency (Hz)	VDD Supply Voltage (Typical) (V)	Response Time (ms)	Packaging
MMA7260Q*	1.5	800	XYZ	350/150	3.3	1	Quad Flat No-Lead (QFN)
	2	600	XYZ	350/150	3.3	1	Quad Flat No-Lead (QFN)
	4	300	XYZ	350/150	3.3	1	Quad Flat No-Lead (QFN)
	6	200	XYZ	350/150	3.3	1	Quad Flat No-Lead (QFN)

*This device has selectable sensitivity (1.5g, 2g, 4g and 6g)

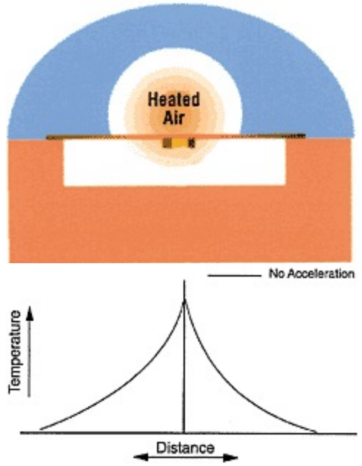
Freescale MMA7260Q

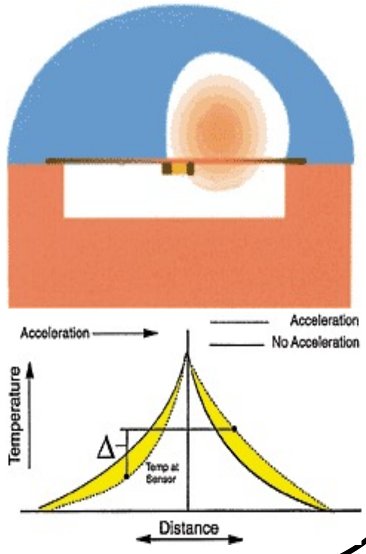
These examples are now old!

- MEMs accelerometers advance very quickly.
- You can now get a digital 3-axis accelerometer that runs continuously on 10-20 microamps (or less!), has an embedded FIFO so uP can sleep, and can interrupt uP on different motions, etc. all at very low cost!
- See Analog Devices, ST Microsystems, etc.
- Examples:
  - ADXL362
- http://www.st.com/web/en/catalog/sense_power/FM89/FM89/SC444/PF259163
- http://www.st.com/web/en/catalog/sense_power/FM89/FM89/SC444/PF262096
- http://www.st.com/web/catalog/sense_power/FM89/SC444/PF261135

Accelerometers: Thermal

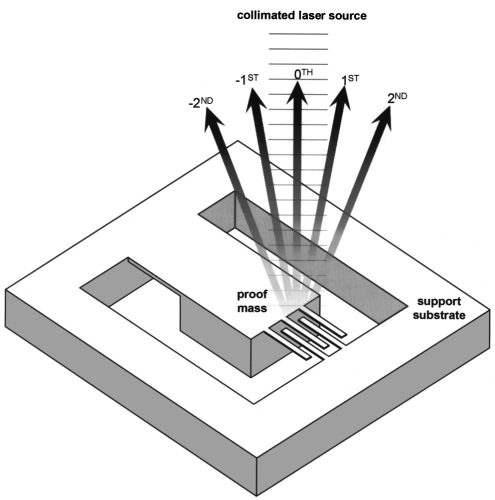
- A heated bubble of air can also act as a proof mass.
- Its shifts with acceleration can be detected by a quadrant of temperature sensors – giving a two-axis system.
- MXR7202GL from MEMSIC (2 axis)
  - Range: ±2g
  - Size: 5mm x 5 mm x 2 mm
  - Bandwidth: 20 Hz
  - Noise: 1.3mg (@20Hz)
  - Cost: $3
  - Pin for pin same as ADXL202

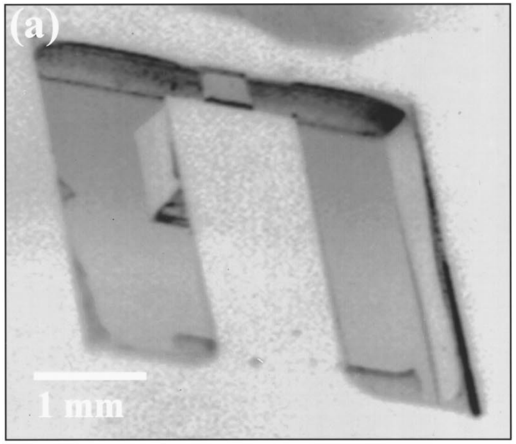




Accelerometers: Interferometric

- Enormously small accelerations can be detected based on interfermetry.
- In the device at right, deflection of the proof mass changes the intensity of the 0^{th} order output
- Resolution of 2µg achieved
- See *Cooper et al* Applied Physics Letters v.76 n.22 for more details





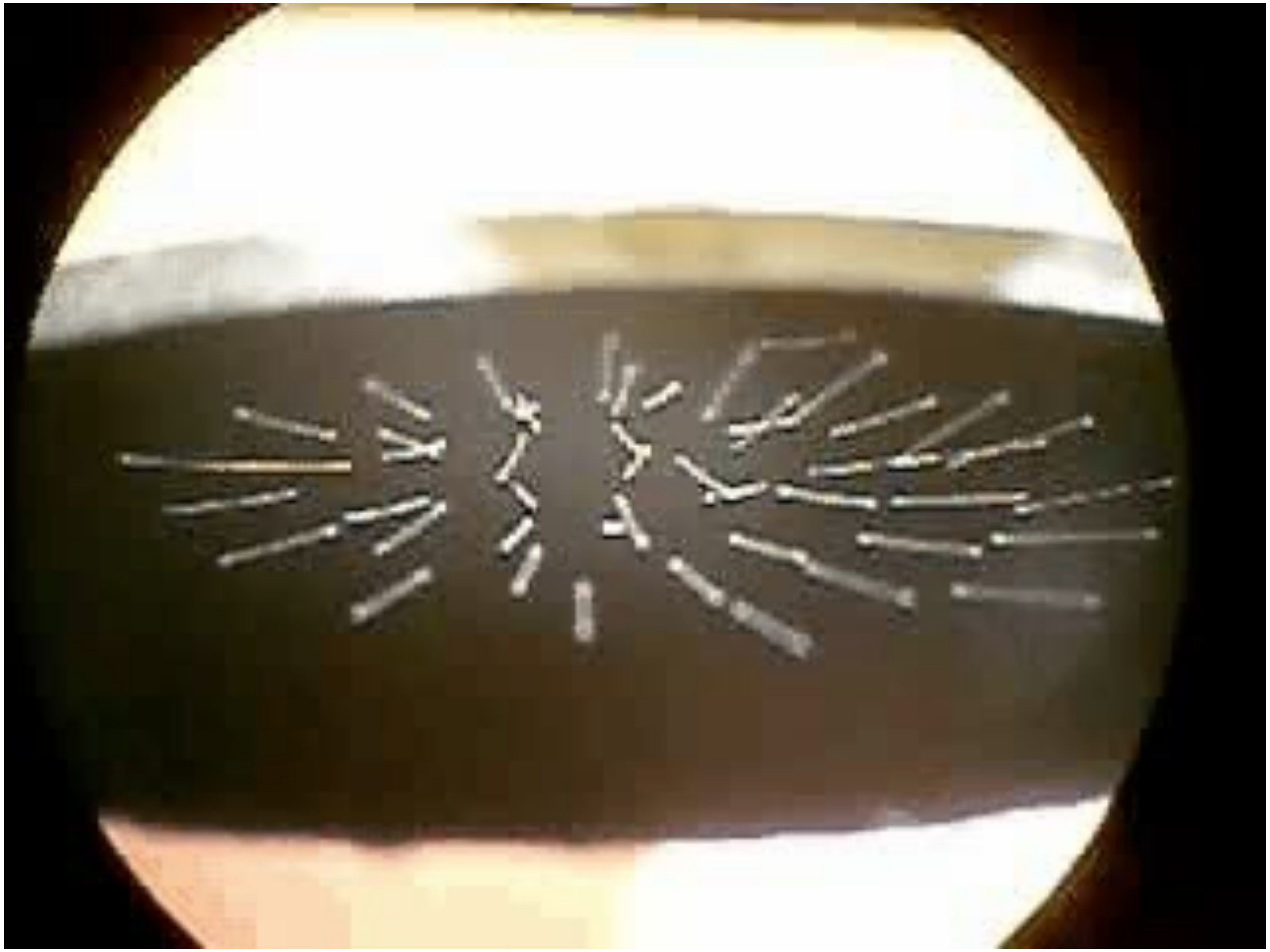
Accelerometers – Particle Trap

- PhD Thesis of Rehmi Post
- Electrostatically suspended multiple charged particles in a tiny homemade electrostatic trap
- Used a video imager to observe orientations and positions
- Ideally particles stay inertially stable, and platform rotates around them
- Particles deflect (“crystal” deforms) under acceleration
- Very preliminary work – many loose ends

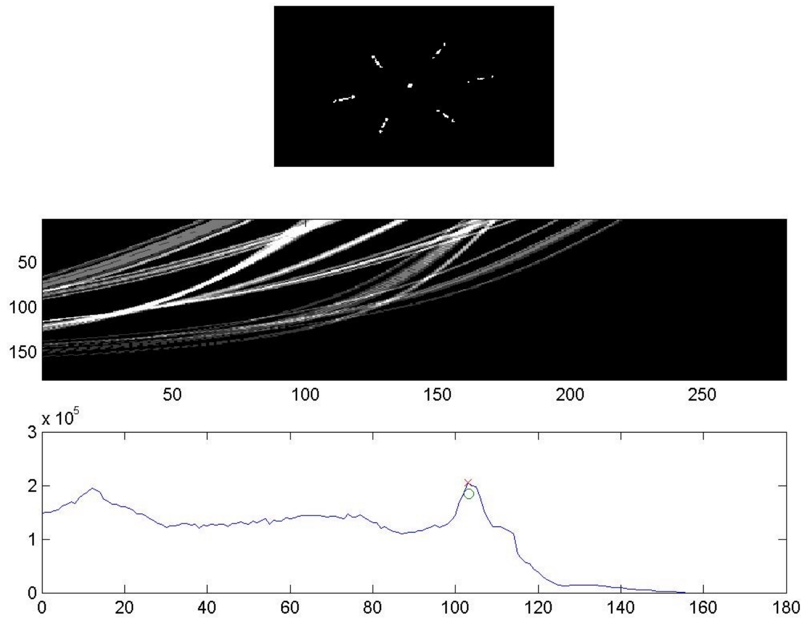
Rehmi's Particle-trap Accelerometer

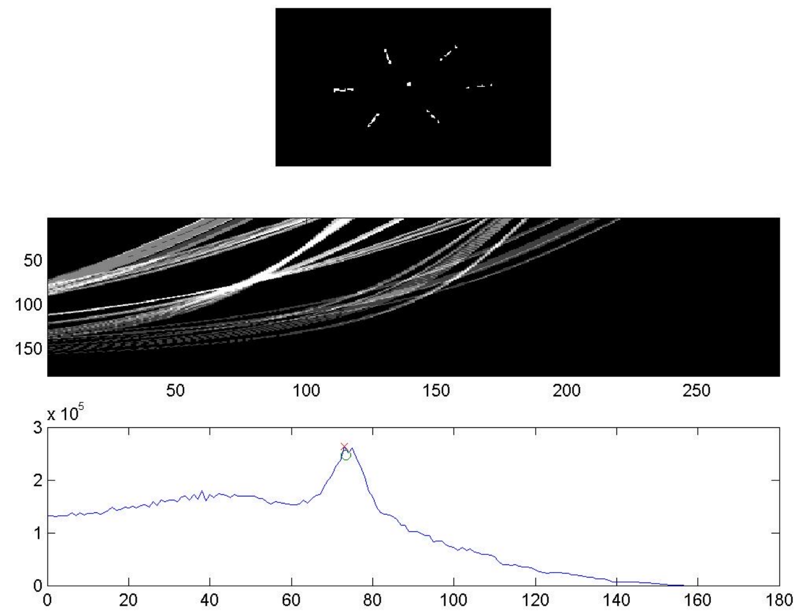
Actual image of oscillating particle clusters in trap

Rehmi’s Levitated IMU in Action



Rotational Hough Analysis





Hough Xform looks at angles of linear structures – peak indicates orientation

Accelerometry Based Applications: Human-Computer Interfaces

Itsy Pocket Computer

http://research.compaq.com/wrl/projects/itsy/

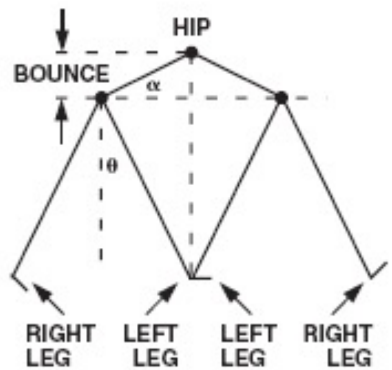
Now in Most Cellphones

Microsoft Sidewinder Joystick

http://www.microsoft.com/hardware/sidewinder/

Now in Nintendo Wii

Accelerometry Based Applications: Pedometry and Body Position



$$Stride \approx \frac{2 \times Bounce}{\alpha}$$

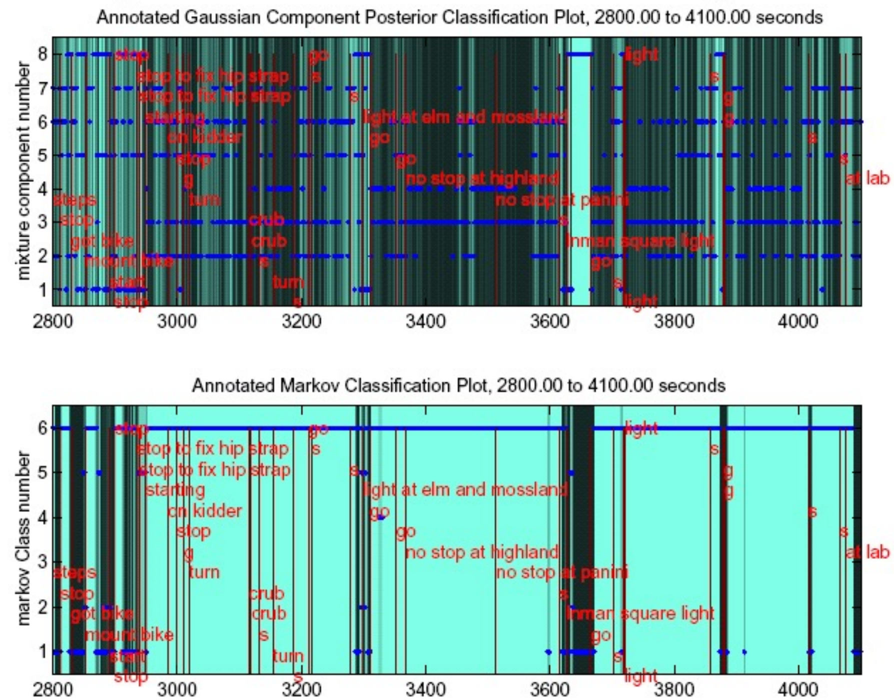
$$Distance \approx \sqrt[4]{A_{max} - A_{min}} \times n \times K$$

where:

- A_{min} is the minimum acceleration measured in the Z axis in a single stride.
- A_{max} is the maximum acceleration measured in the Z axis in a single stride.
- n is the number of steps walked.
- K is a constant for unit conversion (i.e., feet or meters traveled).

Analog Devices App. Note 602

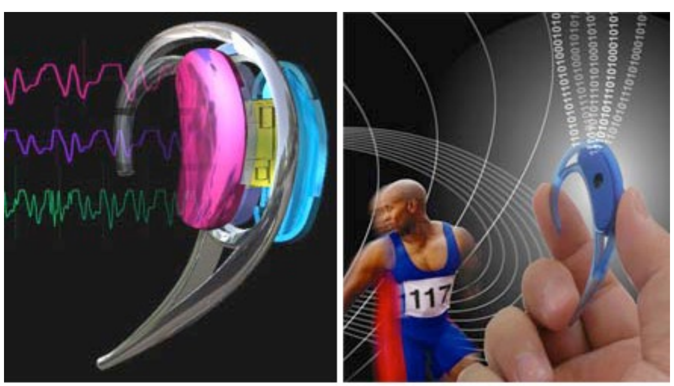
Figure 12: Results of classification for "Biking" data.



Real-Time Motion Classification for Wearable Computing Applications

http://www.media.mit.edu/~rich

Accelerometers Fuel Quantified Self Fitness Revolution

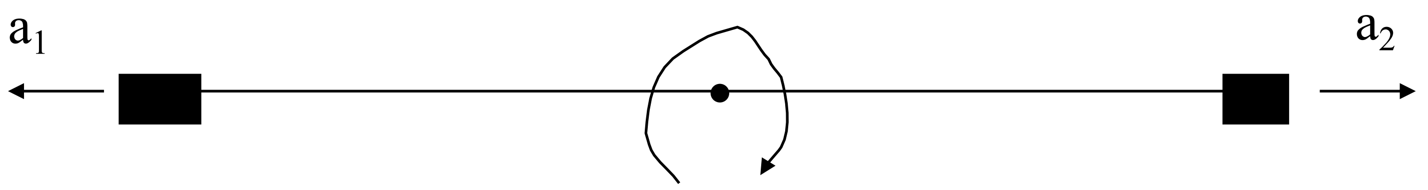


Imperial College Earpiece

Many algorithms now to determine and measure user’s activity & state

GYROSCOPES

"Gyro" from Displaced Accelerometers



- Sum is gravity – difference is acceleration.
- Need large lever arm for accuracy
  - Must subtract out gravity, etc.

Principles of Angular Velocity

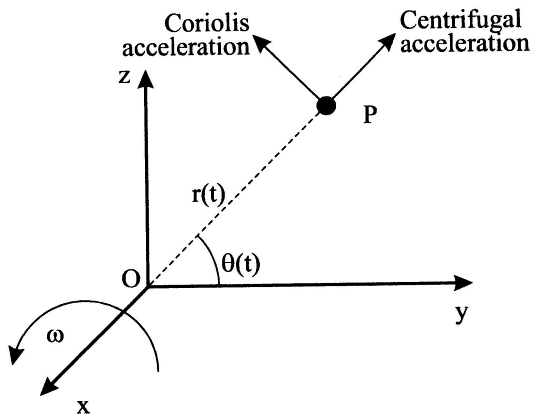
- Angular velocity (ω) is the first derivate of angle with respect to time ($\dot{\theta}$)
- Note the relationship between angular velocity and translational velocity (instantaneous)
  - $v = \omega \times r$
- Angular momentum, like translational momentum, is conserved
  - Figure skater (change in momentum of inertial)
  - Toy gyroscope (would have to change ω to fall)
  - Precessional Torque is $\tau = \omega \times H$

Angular Momentum

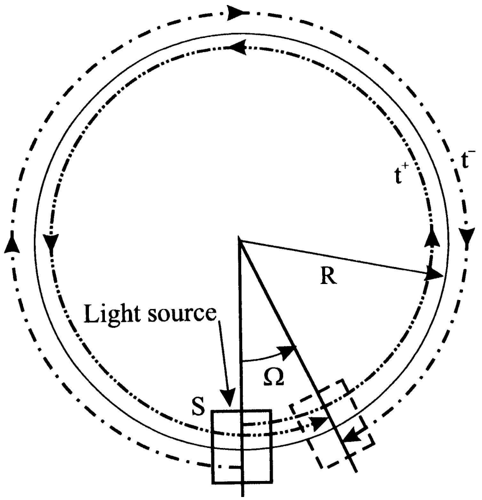
Body Rotation

Principles of Gyroscopes

- The Coriolis force is a fictitious force exerted on a body when it moves in a rotating reference frame. (see video)
  - $F_c = 2v\omega$



- The Sagnac effect is the change in path length experienced by light traveling in a rotating reference frame.
  - $\phi = (8\pi AN/\lambda c)\Omega$



Gyroscope Accuracy Scaling

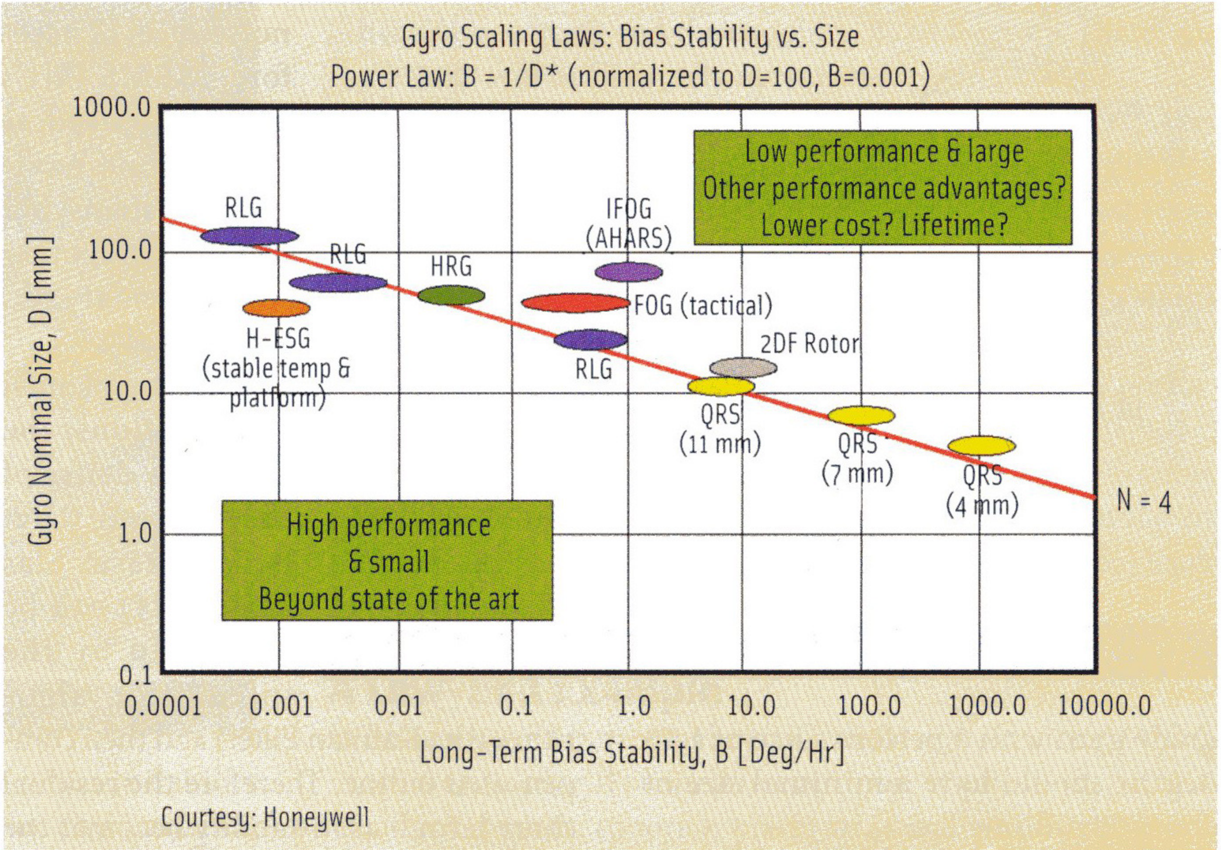
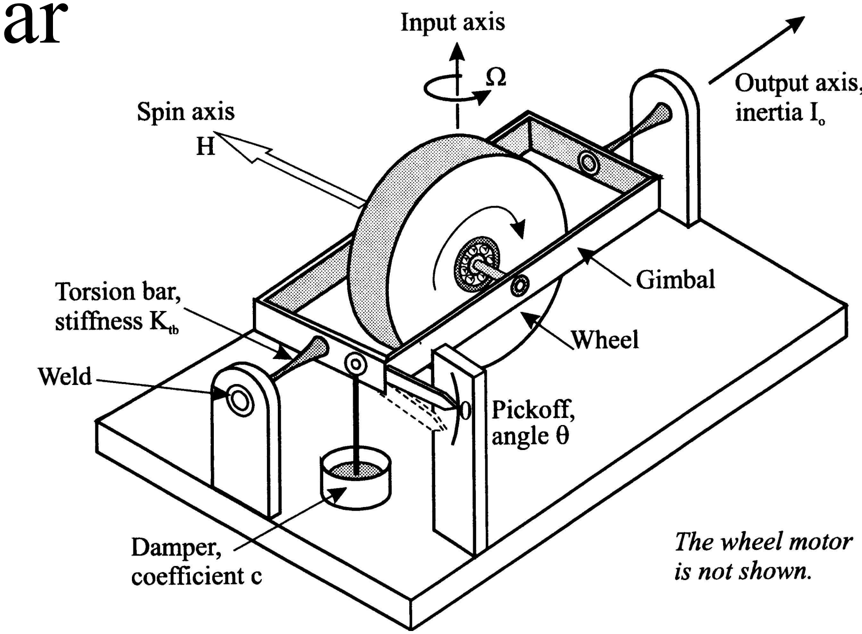


FIGURE 1 Bias Stability vs. Nominal Size for Mature Gyro Technology.

- From InsideGNSS (March/April 07)
- Doesn't go to down classified systems (e.g., Draper floated gyros)

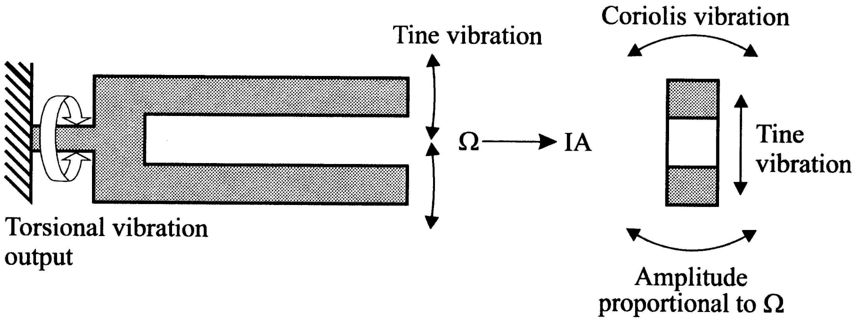
Gyroscopes: SDFG

- The simplest mechanical gyroscopes, the single degree of freedom gyroscope consists of a rotating wheel attached to torsion bars
- Rotation perpendicular to the axis of the wheel will cause a deflection due to the Coriolis force



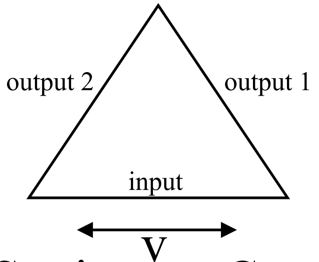
Gyroscopes: Tuning Fork

- The tuning fork gyroscope was designed to be a much simpler mechanical structure than SDFG.
- Consists of two masses, connected to a common base, oscillating out of phase with each other. Note that there is therefore no net motion.
- Output is proportional to tine velocity and input rotational rate, and is usually measured as a twist at a stiff base

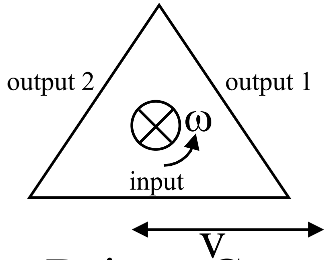


Gyroscopes: Vibrating Reed

- This technique is quite similar to the tuning fork gyroscope, and uses piezoelectrics both as input and output
- A central vibrating reed drives two others, creating equal piezoelectric output.
- A rotation deflects the velocity, driving one reed more than the other, creating a differential output



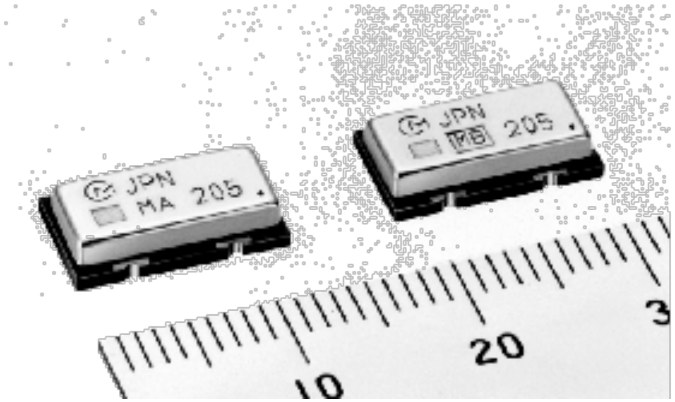
Stationary Case



Driven Case

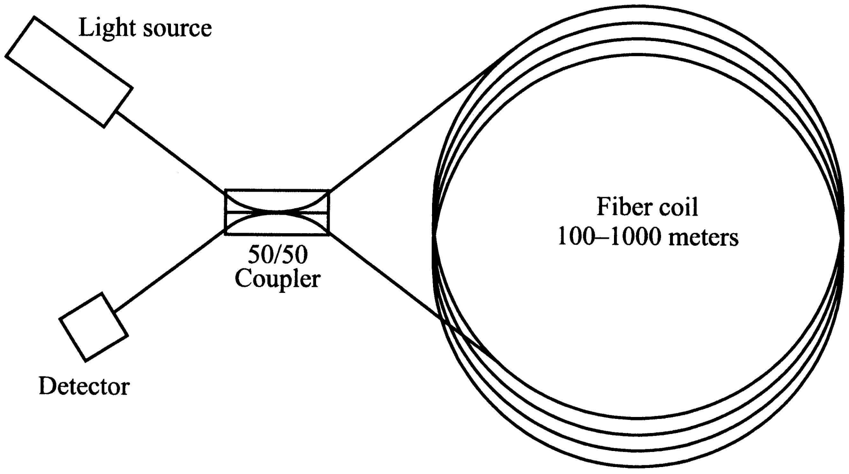
Gyroscopes: Murata ENC03J

- ENC03J from Murata (1 axis)
  - Range: ±300^{o}/sec
  - Size: 0.6in x 0.3in x 0.2in
  - Bandwidth: 50 Hz
  - Noise: 0.5^{o}/sec (@50 Hz)
  - Cost: $40



Gyroscopes: Interferometric

- Interferometric gyroscopes rely on the Sagnac effect in light travelling in very long loops (usually a small package with many turns).
- Rotation causes a phase difference, which can be converted to a magnitude by mixing the signals
- Suffer from reflection and limited by shot noise

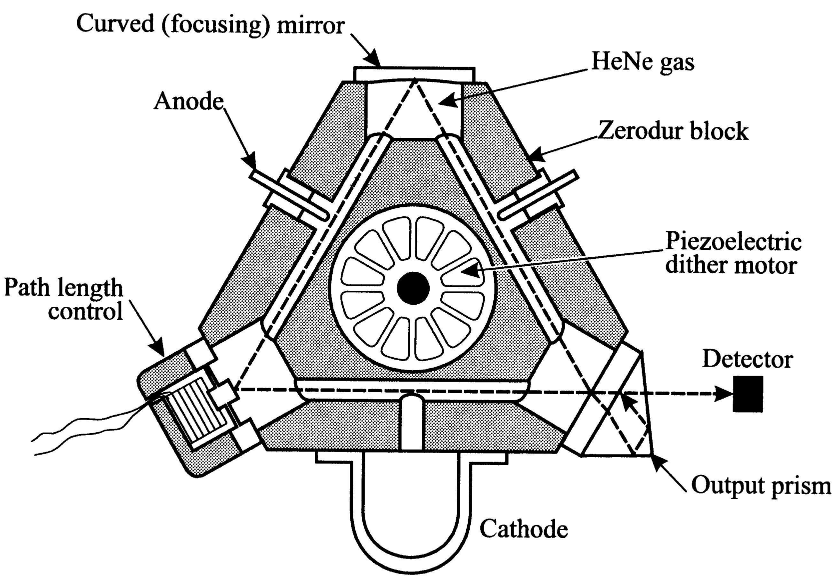


Gyroscopes: Fizoptika VG941-3AS

- VG941-3AS from Fizoptika (1 axis)
  - Range: ±600°/sec
  - Size: 50mm x 24mm dia
  - Bandwidth: 1 kHz
  - Noise: 0.01°/sec (@50 Hz)
  - Cost: $1300

Gyroscopes: Ring Laser

- Ring laser gyros achieve far better results than IFOGs in a smaller volume by creating a loop within a lasing resonator.
  - Finite number of wavelengths must fit in cavity, hence lasing frequency must change with rotation
- Suffer from lock-in due to scatter and coupling



- These gyros achieve tactical performance levels
  - Military, aviation, spacecraft

Gyroscopes – Wineglass (or hemispherical resonator)

- Standing wave modal pattern of vibrations in a shell is perturbed by rotation
  - Wave propagation velocities around shell are unequal in the presence of rotation
  - Coriolis force effect

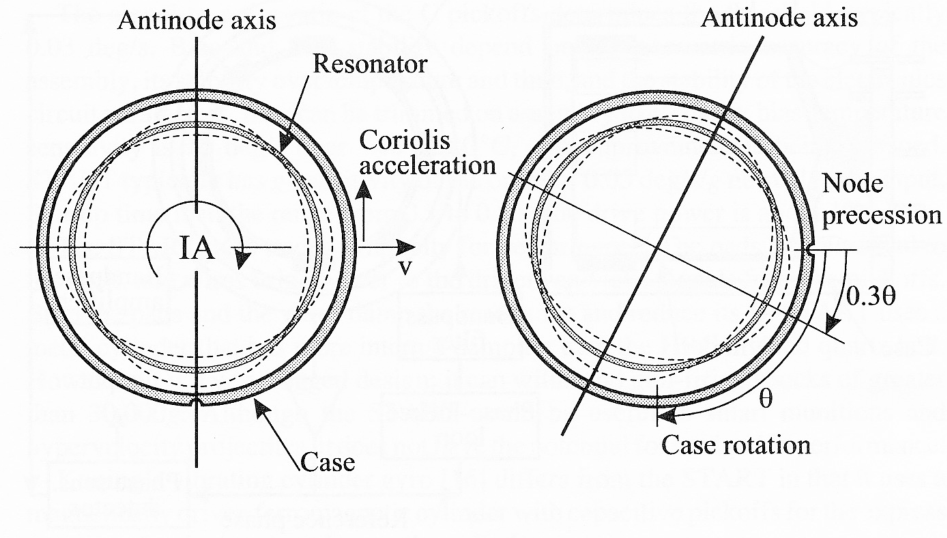
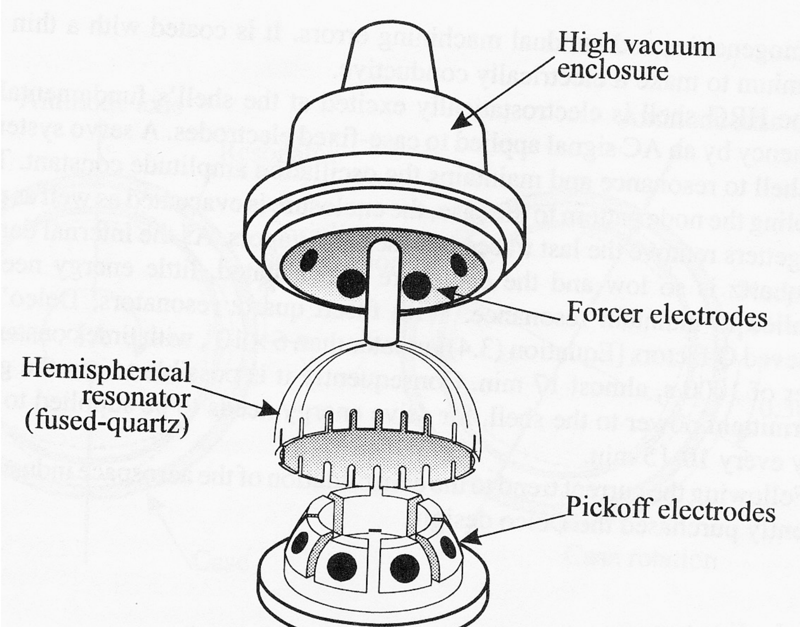
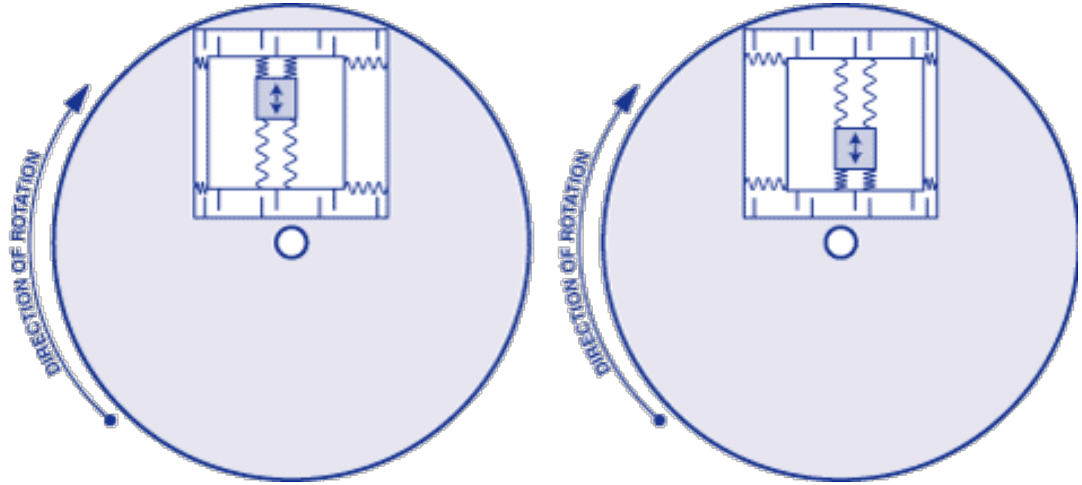


Figure 10.8. Precession of HRG antinodes.



Gyroscopes: MEMS

- Several companies now make MEMS gyros
  - Analog Devices, Delphi, ST Microelectronics, Silicon Sensing Systems, Applied MEMS, Invensense inc.
- Analog Devices now makes a MEMS gyroscope very similar in principle to their MEMS accel
- An oscillating mass with capacitive fingers is driven relative to fixed finger on the substrate
- Perpendicular rotating will create an imbalance



Gyro Power!

- Note that Gyros take much more power than accelerometers
- Mechanical gyros need excitation (rotation), which is significant in terms of energy even for Hi-Q MEMs
- Currently, gyros are stuck at around 1 mA.

MEMS Implementation

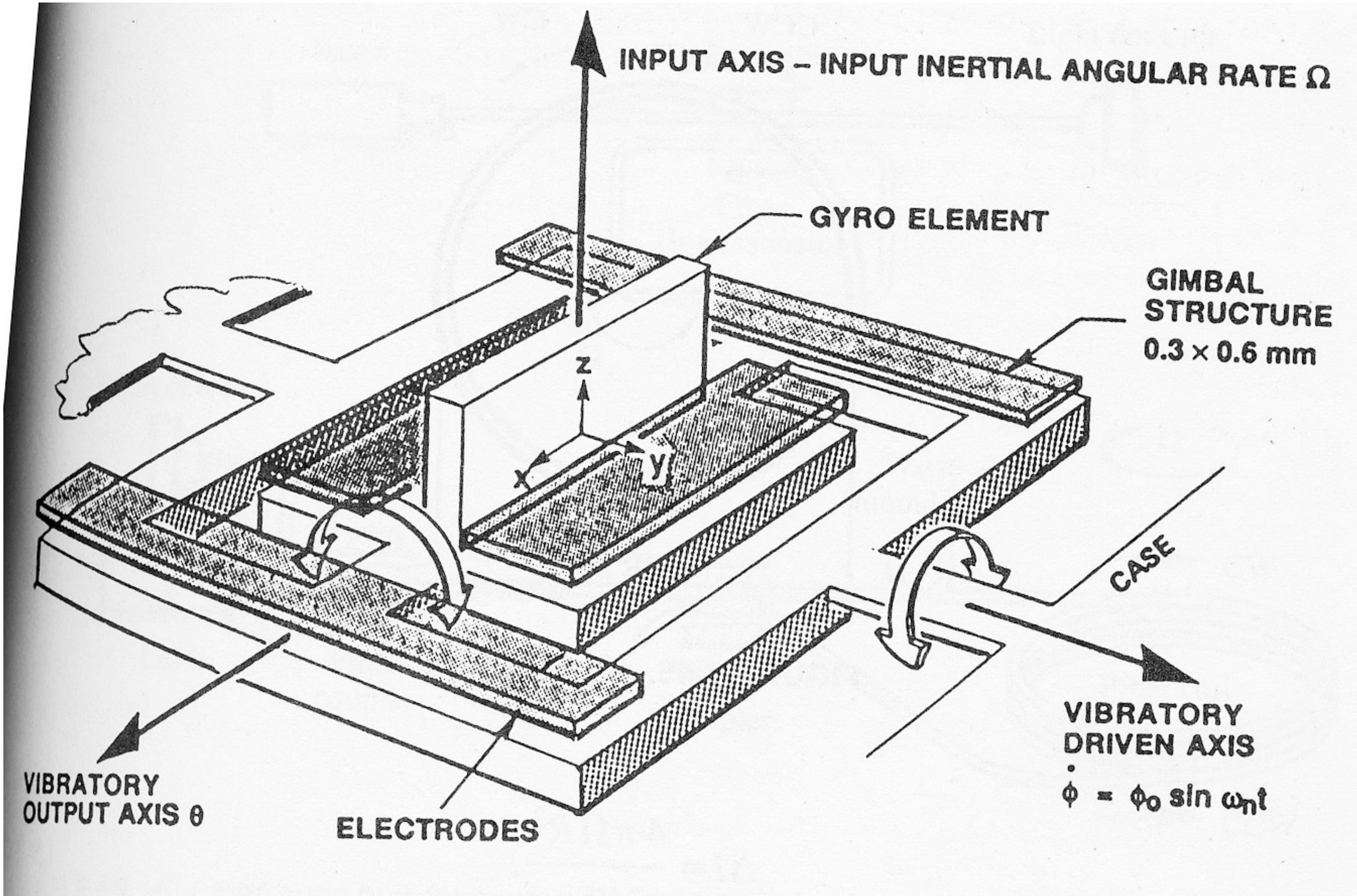
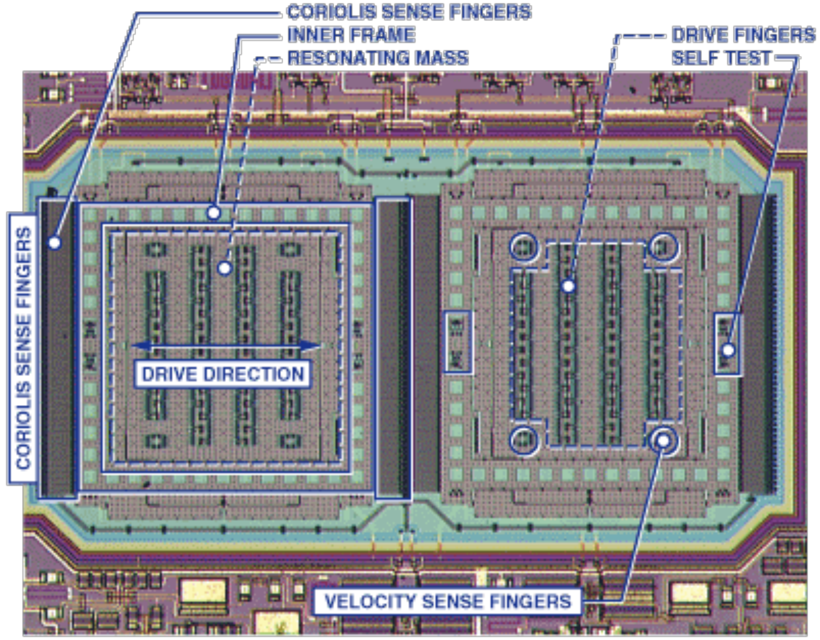


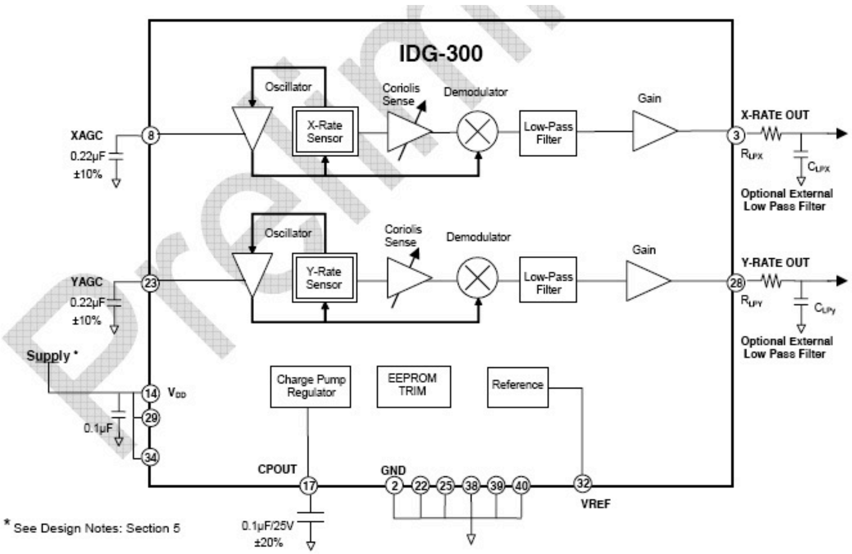
FIGURE 5.44. Vibratory rate gyro concept (from [14]).

Gyroscopes: Analog Devices ADXRS300

- ADXRS300 from Analog Devices (1 axis)
  - Range: ±300°/sec
  - Size: 7mm x 7mm x3mm
  - Bandwidth: 40 Hz
  - Noise: 0.6°/sec (@40 Hz)
  - Cost: $33



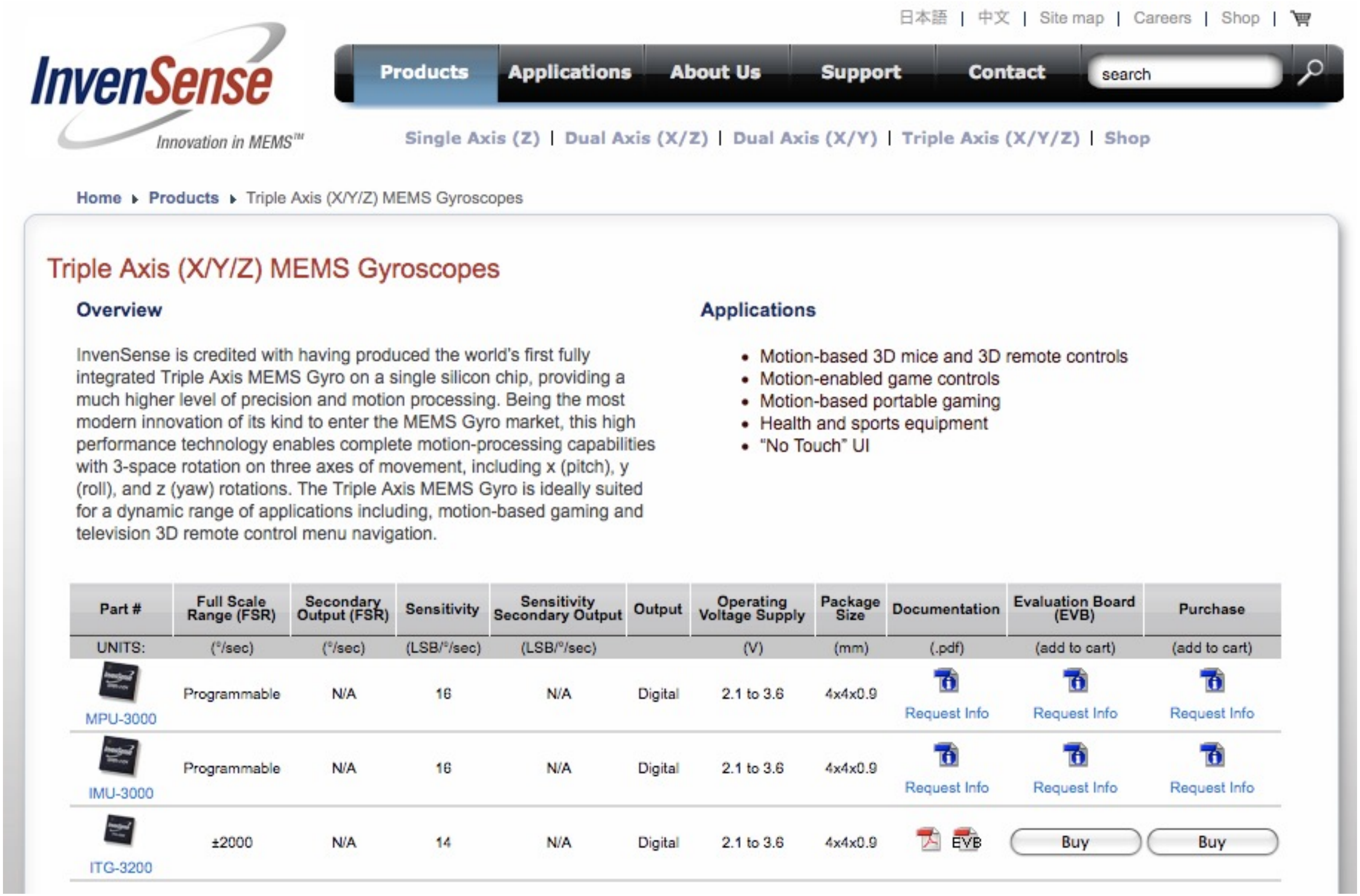
IDG 300, 500 and IDG 1000 series Dual axis gyros from InvenSense



It's a race - 2 axis, 3 axis gyros then integrated IMUs

Parameters	Typical Specifications	Units
Full Scale Range	500	°/sec
Sensitivity	2.0	mV/(°/sec)
Reference Voltage	1.23	V
Zero Rate Output	1.5	V
Nonlinearity	<1	% FS
Cross Axis Sensitivity	±2	%
Power Supply	3.3	V
Power Consumption	9.5	mA
Startup Time	200	ms
Specified Temp Range	0 to +70	°C
Weight	0.14	g
Parameters	**Absolute Maximum Ratings**	**Units**
Power Supply Voltage	-0.3 to +6.0V	V
Shock (any axis, unpowered)	5000	g for 0.3ms
Storage Temp Range	-40 to +125	°C

Invense 3-axis Gyros



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Triple Axis (X/Y/Z) MEMS Gyroscopes

Overview

InvenSense is credited with having produced the world's first fully integrated Triple Axis MEMS Gyro on a single silicon chip, providing a much higher level of precision and motion processing. Being the most modern innovation of its kind to enter the MEMS Gyro market, this high performance technology enables complete motion-processing capabilities with 3-space rotation on three axes of movement, including x (pitch), y (roll), and z (yaw) rotations. The Triple Axis MEMS Gyro is ideally suited for a dynamic range of applications including, motion-based gaming and television 3D remote control menu navigation.

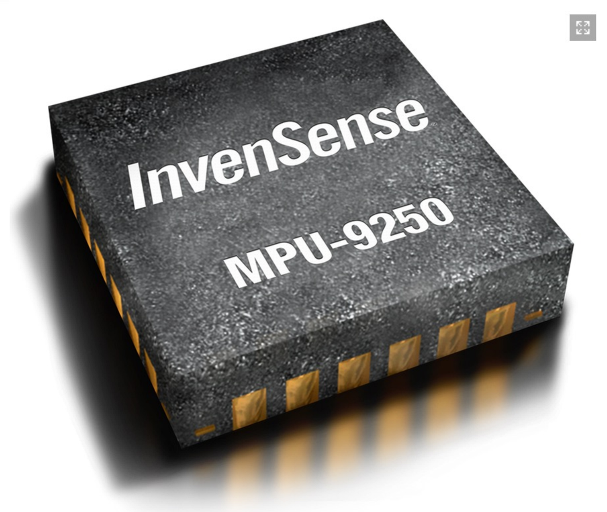
Applications

- Motion-based 3D mice and 3D remote controls
- Motion-enabled game controls
- Motion-based portable gaming
- Health and sports equipment
- "No Touch" UI

Part #	Full Scale Range (FSR)	Secondary Output (FSR)	Sensitivity	Sensitivity Secondary Output	Output	Operating Voltage Supply	Package Size	Documentation	Evaluation Board (EVB)	Purchase
UNITS:	(°/sec)	(°/sec)	(LSB/°/sec)	(LSB/°/sec)		(V)	(mm)	(.pdf)	(add to cart)	(add to cart)
MPU-3000	Programmable	N/A	16	N/A	Digital	2.1 to 3.6	4x4x0.9	Request Info	Request Info	Request Info
IMU-3000	Programmable	N/A	16	N/A	Digital	2.1 to 3.6	4x4x0.9	Request Info	Request Info	Request Info
ITG-3200	±2000	N/A	14	N/A	Digital	2.1 to 3.6	4x4x0.9	EVB	Buy	Buy

- Integrated IMU came soon.

Invensense Smart 9-Axis Integrated 'IMU'



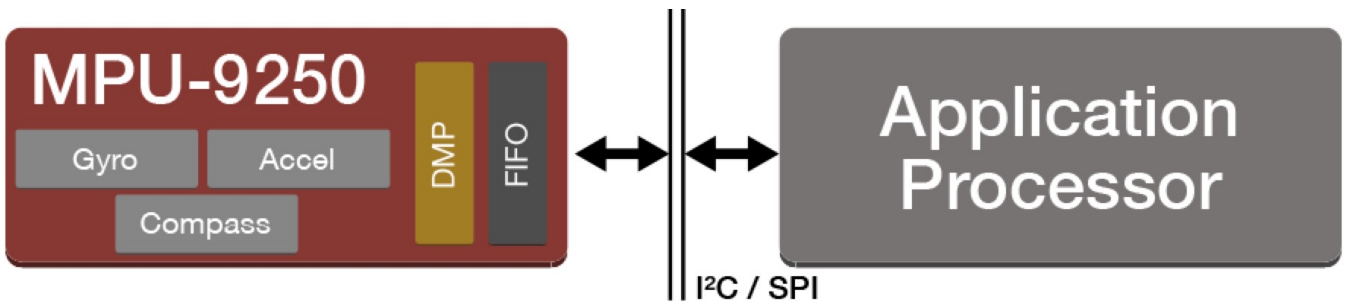
MPU-9250 Nine-Axis (Gyro + Accelerometer + Compass) MEMS MotionTracking™ Devices

http://invensense.com/mems/gyro/mpu9250.htm

InvenSense Nine Axis Gyroscope + Accelerometer + Compass with Embedded Digital Motion Processor

1/2

CLOSE



MPU-9250 System Diagram

2/2

CLOSE

MARG Device

The 6000 series parts don't have the magnetometer, but can be set up to control an external one (this is what's in the WristQue).http://invensense.com/mems/gyro/mpu6050.html

Micropower Rotation Processing Engines

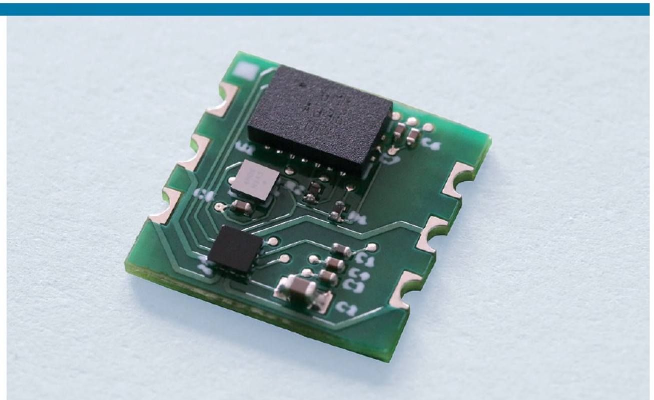
EM MICROELECTRONIC

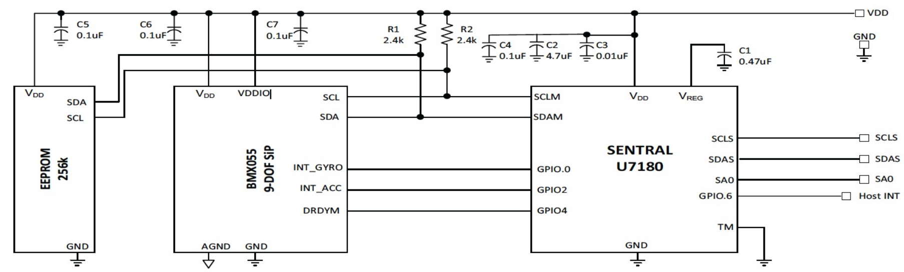
A COMPANY OF THE SWATCH GROUP

FACT SHEET | EM7180SFP

Subject to change without notice
Version 1.0, 4-March-15

www.emmicroelectronic.com





Ultra Low Power Sensor Fusion Platform

The Sensor Fusion Platform (SFP) is small form factor integrated module containing a EM7180 SENtral Sensor Fusion Coprocessor, BMX055 9-degree-of-freedom (9-DOF) system in a package (3-axis gyroscope/accelerometer/ magnetometer) and a ST24256 32KB EEPROM containing the module firmware.

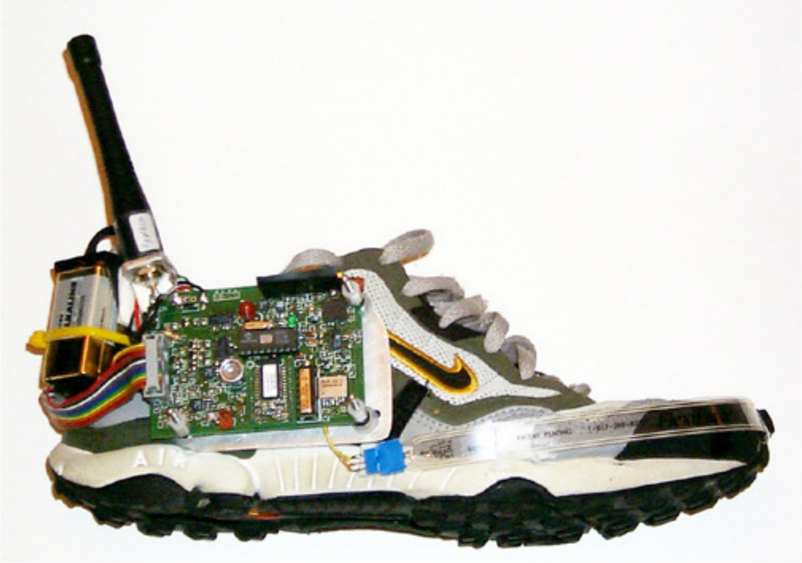
The SENtral Sensor Fusion Coprocessor fully controls and processes data from BMX055 9-DOF sensor. The primary data output from SFP are quaternions, which uniquely define device orientation, or Euler angles (heading, pitch, and roll). The quaternions easily can be also converted to the rotation vector, and the rotation matrix. Raw or calibrated sensor data are also provided to external Host which can control individual sensor rates and power states of the platform. External Host CPU can communicate with the SFP over high-speed I2C bus and obtain both fusion result and raw sensor data.

Supply Current

Parameter	Symbol	Conditions	Typ	Unit
Moving - with ative gyro	IDDM	VDD=2.4V	7.9	mA
Still - with active accelerometer	IDDST	VDD=2.4V	300	µA

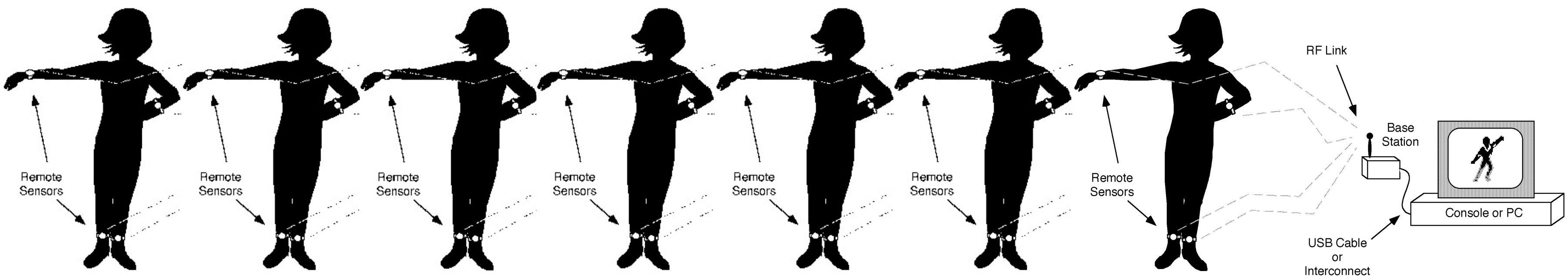
CH-based, from watch industry – calculates continuous rotation from IMU
Includes 9-DOF IMU

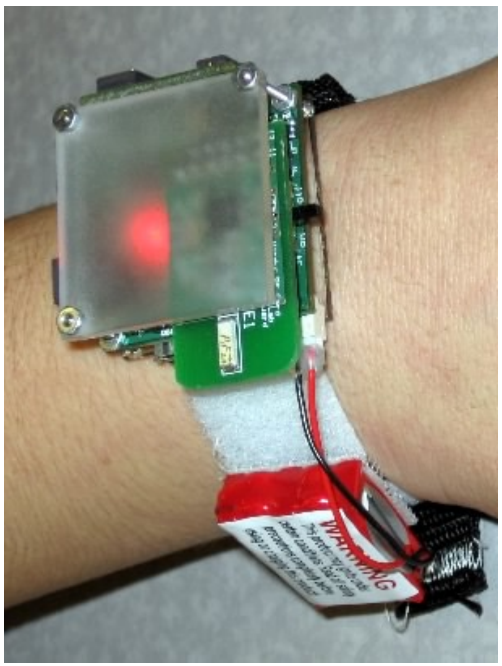
A Brief Interlude: Expressive Footwear

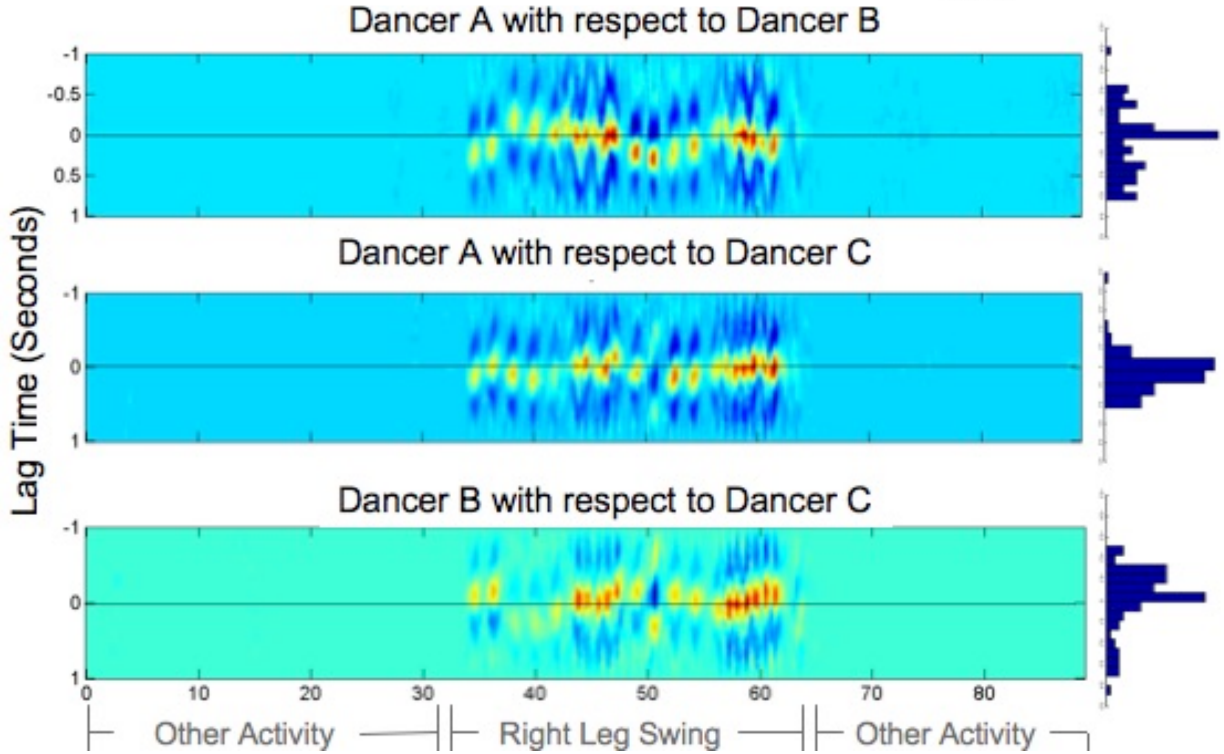


http://www.media.mit.edu/resenv/danceshoe.html

Scaling to several dancers…







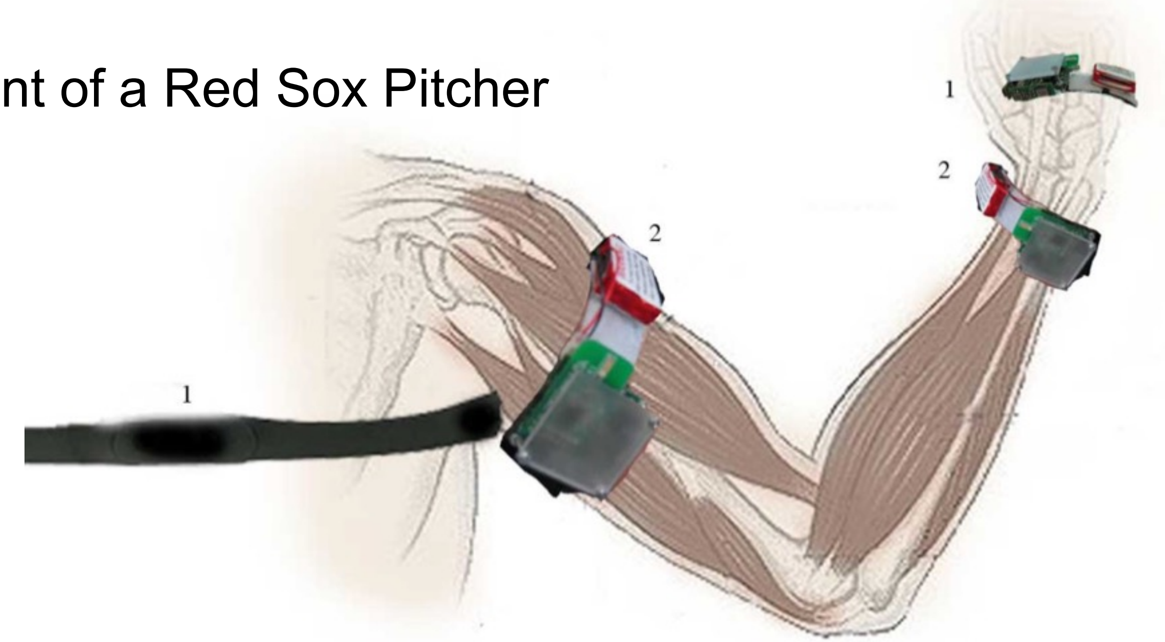
Capacitive proximity to 50 cm
6-axis IMU - 1 Mbps TDMA radio
100 Hz Full State Updates from 25 nodes

High Speed Sensor Fusion
Vocabulary of features

Mid-March Diversion to Ft. Meyers, FL

Red Sox Spring Training - March 2006

Biomotion measurement of a Red Sox Pitcher



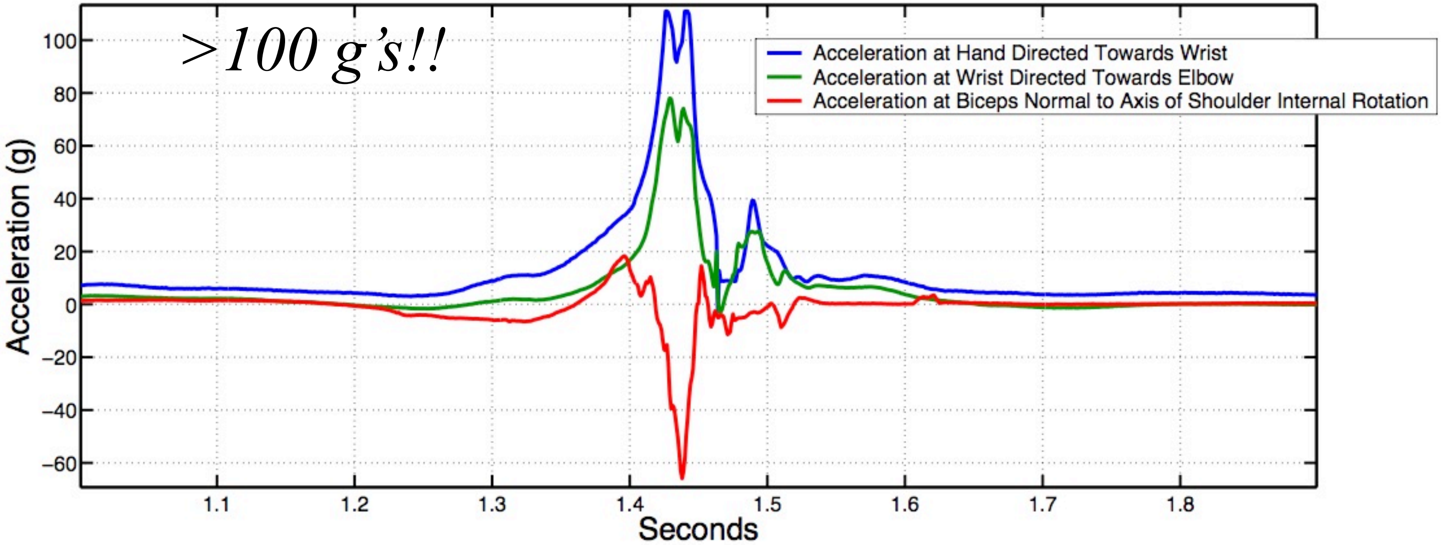
Modified sensors for high range and high sample rates

- 1kHz sampling with data logged to flash memory
- Torso - Single IMU with 10g accelerometer, 1500 deg/sec gyro
- Upper Arm - Double IMU
  - 10g accel, 1500 deg/sec gyro
  - 70g accel (ADXL78), 10000 deg/sec gyro
- Wrist - Double IMU
  - 10g accel, 1500 deg/sec gyro
  - 120g accel (ADXL193), 10000 deg/sec gyro
- Hand - Single IMU with 120g accelerometer, 10000 deg/sec gyro

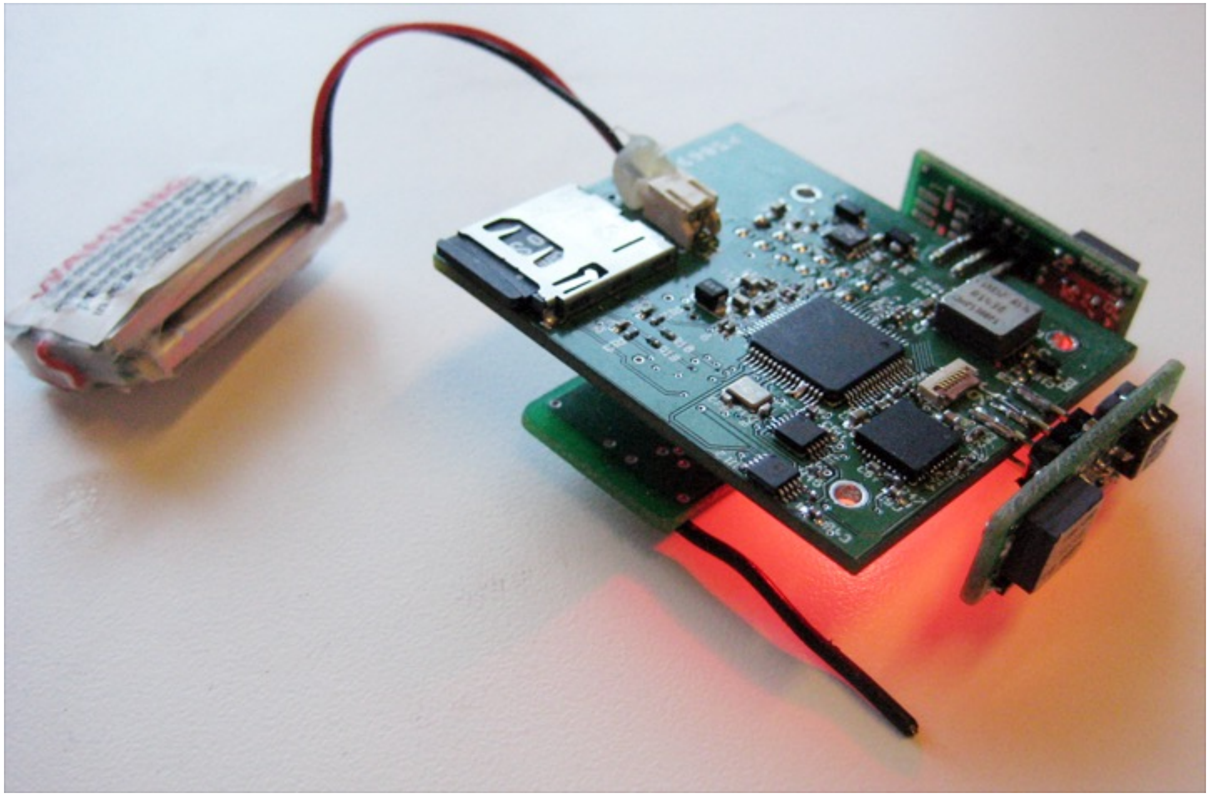
Preliminary Results - Red Sox Spring Training

- Acceleration at the wrist peaks well above 100g
- Most of this acceleration occurs in a 30ms window
- Equates to 30 samples for the modified inertial system, but only 5 frames on a 180Hz video capture system

Acceleration Phase of the Pitch Above Captured at Three Critical Locations - Hand, Wrist, and Biceps



Return to Spring Training, 3/09



New device has onboard removable flash for continual data storage (RF synch), Bi-range full IMU

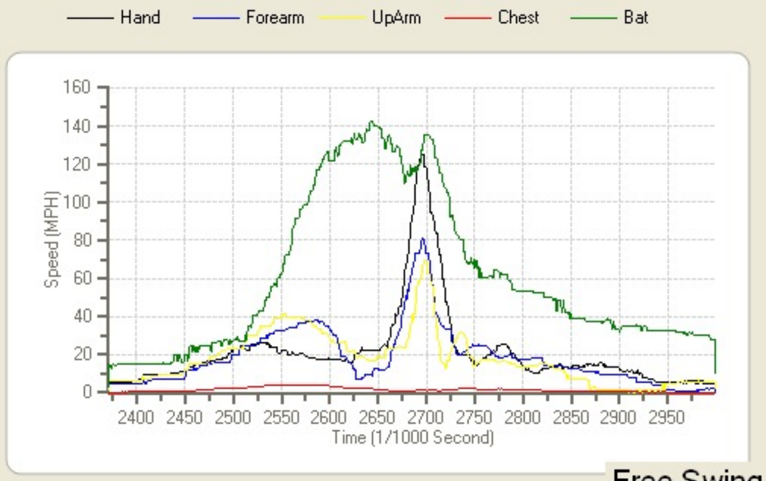
Joe Paradiso / ResEnv

Soon measuring entire team and streaming data to MIT/MGH

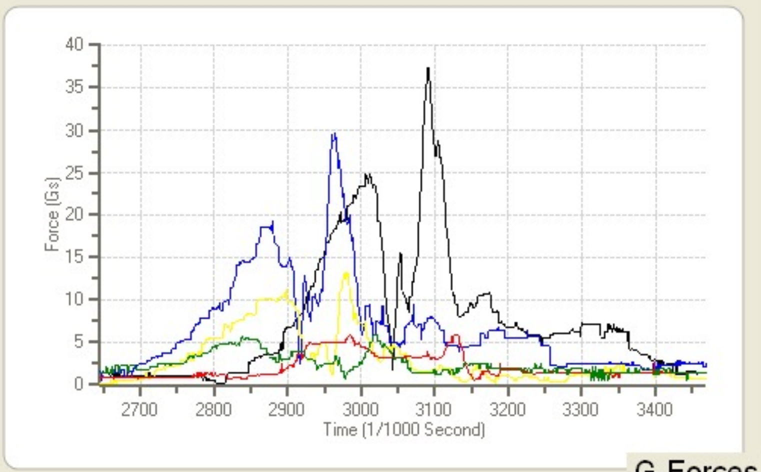
Batter: Gentile , Zack

Print

	Peak Bat Speed	Peak Hand Speed	Timing Bat vs Hand	Peak Forearm Speed	Peak Chest Speed	Hand Speed @ Impact	Bat Speed @ Impact	Swing Duration	Efficiency
Free Swing	165.25 +/- 9.91	70.13 +/- 6.53	26.75 +/- 14.70	42.25 +/- 2.87	2.25 +/- 0.46			554.00 +/- 232.27	
Impact		72.22 +/- 6.47		44.17 +/- 2.36	2.56 +/- 0.51	27.28 +/- 5.21	64.37 +/- 12.30	1,140.00 +/- 1,070.87	103.14
All	163.25 +/- 10.89	70.46 +/- 6.36	25.25 +/- 18.55	43.19 +/- 2.76	2.46 +/- 0.51	27.28 +/- 5.21	64.37 +/- 12.30	960.00 +/- 960.48	

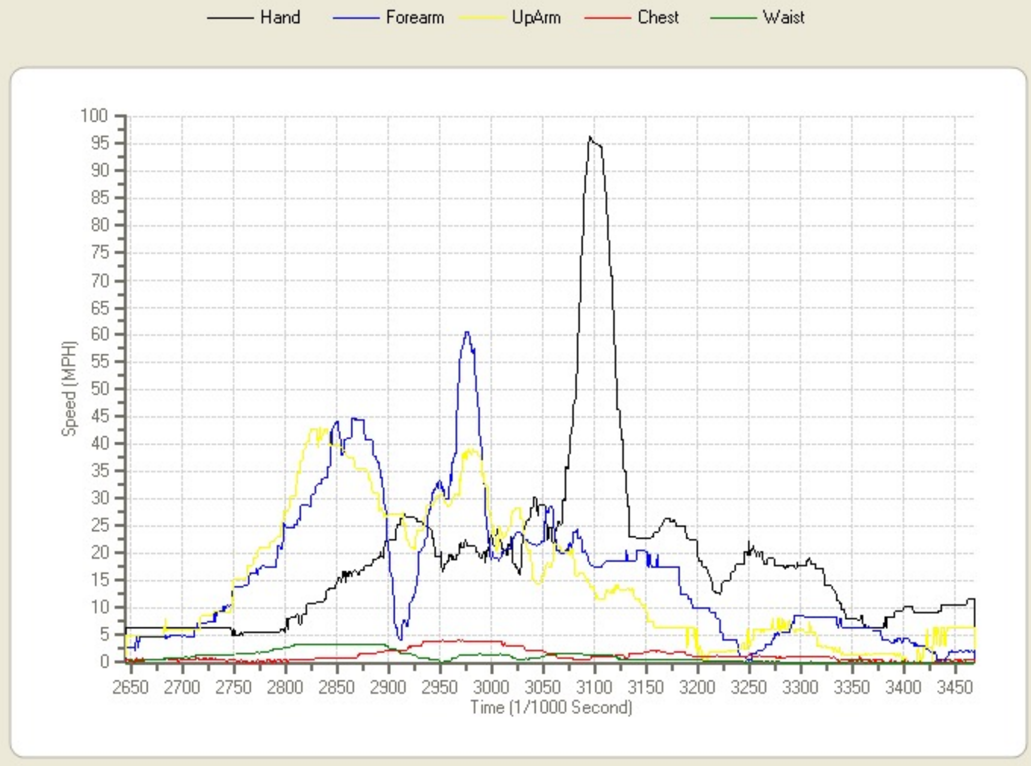


Free Swing



G-Forces

Hit/Impact Swing



Michael Lapinski, Clemens Satzger

MGH 1811

Device Details – Spinner Social Sensor

- Wearable on collar or as pin/badge
- Audio system with DSP for analytics and CD quality recording
- Mini-SD Slot for copious memory
- Compass for orientation
- 3-axis Accelerometer & 2-Axis Gyro
- IR communication and line of sight detection/proximity
- 802.15.4 Radio with RF Location engine
- Captures social signal and group dynamics
- New Badge has OLED Display

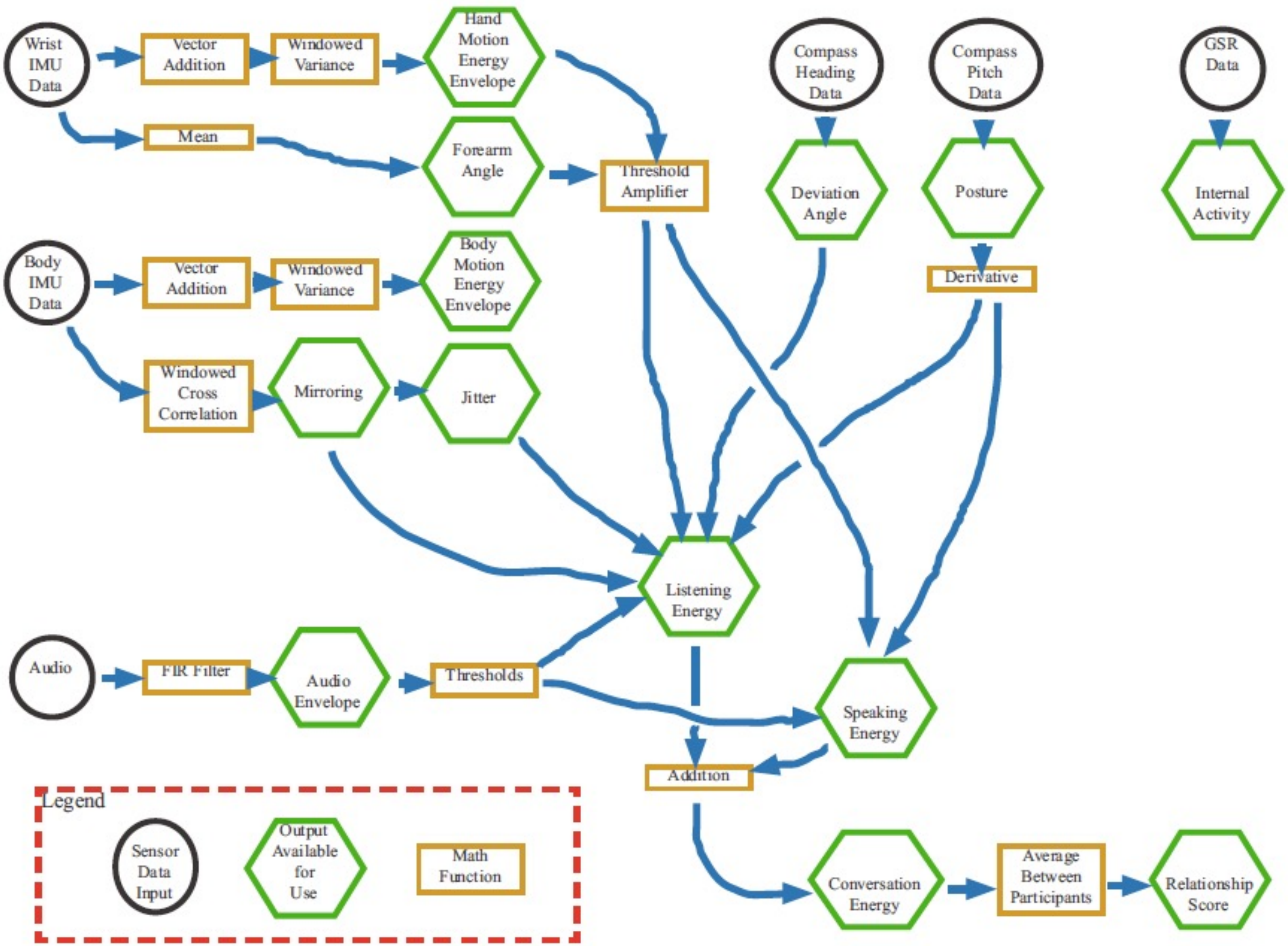
SPINNER Project - Mat Laibowitz

Device Details – Spinner Wrist Sensor

- Wrist worn device
- 3-axis Accelerometer
- Galvanic Skin Response (GSR) Sensor
- Location engine
- UI for interacting with network
- Stores and plays videos, providing ownership of video to end user
- Captures gesture and indications of affective state

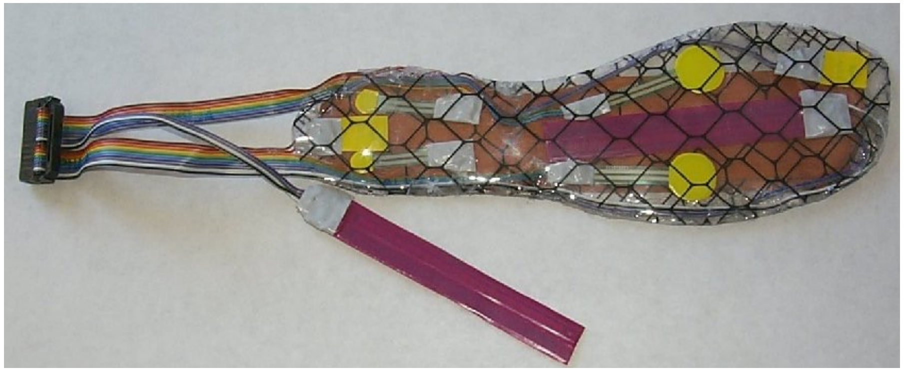
SPINNER Project - Mat Laibowitz

Spinner High-Level Feature Extraction



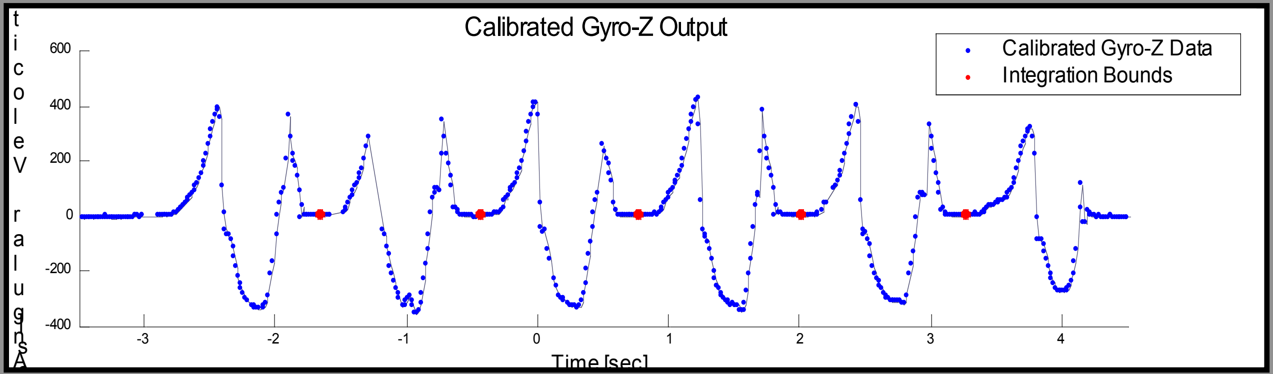
IMU Based Applications: Medical Data Collection

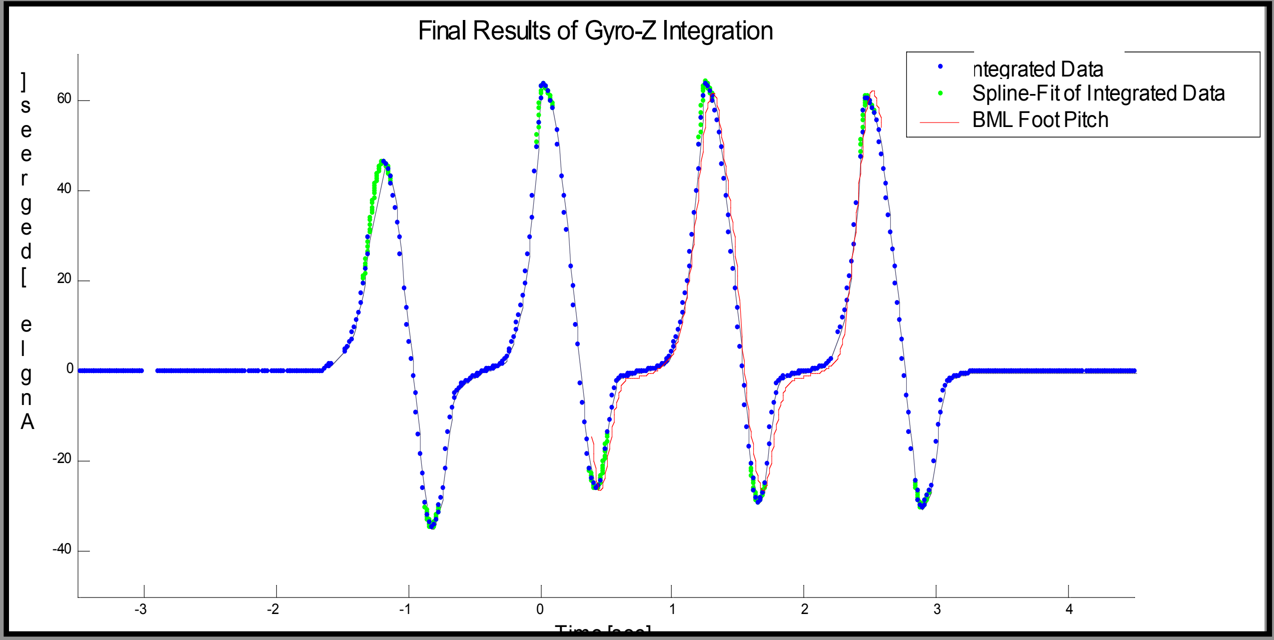
- Gait Shoe



http://www.media.mit.edu/resenv/GaitShoe/

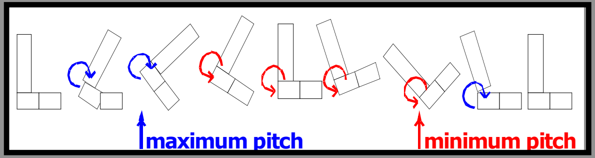
Reconstructed Foot Pitch





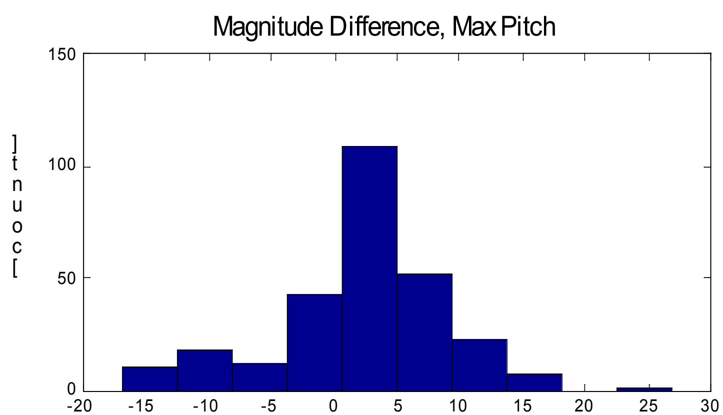
Z-gyroscope integrated once with respect to time, over a single leg swing.

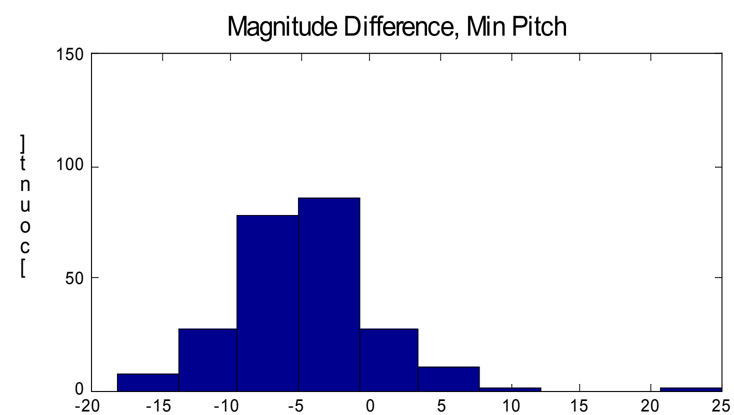
[zero offset adjusted, iteratively, per integration].



Foot Pitch Results

Comparison	Difference		Percent Change [%]		Samples
	Mean	Std Dev	Mean	Std Dev	
Shoe Pitch Max minus BML Pitch Max	1.9°	6.7°	4.22	10.4	279
Time of Shoe Pitch Max minus Time of BML Pitch Max	-.04 sec	.02 sec			279
Shoe Pitch Min minus BML Pitch Min	-4.9°	5.1°	29.1	20.5	241
Time of Shoe Pitch Min minus Time of BML Pitch Min	-.01sec	.02 sec			241

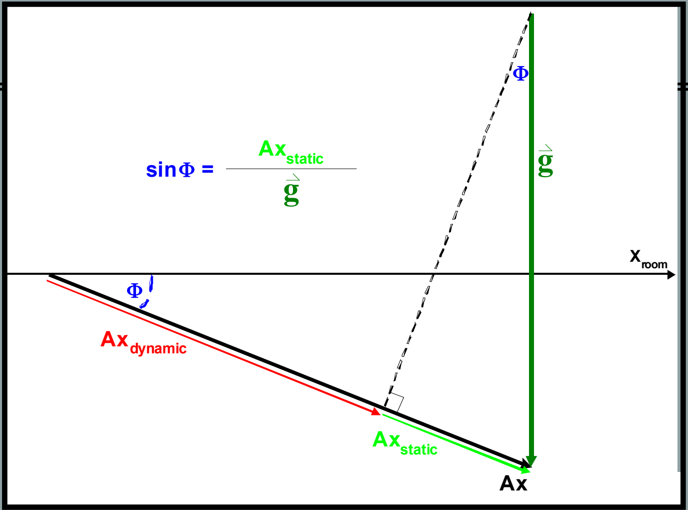


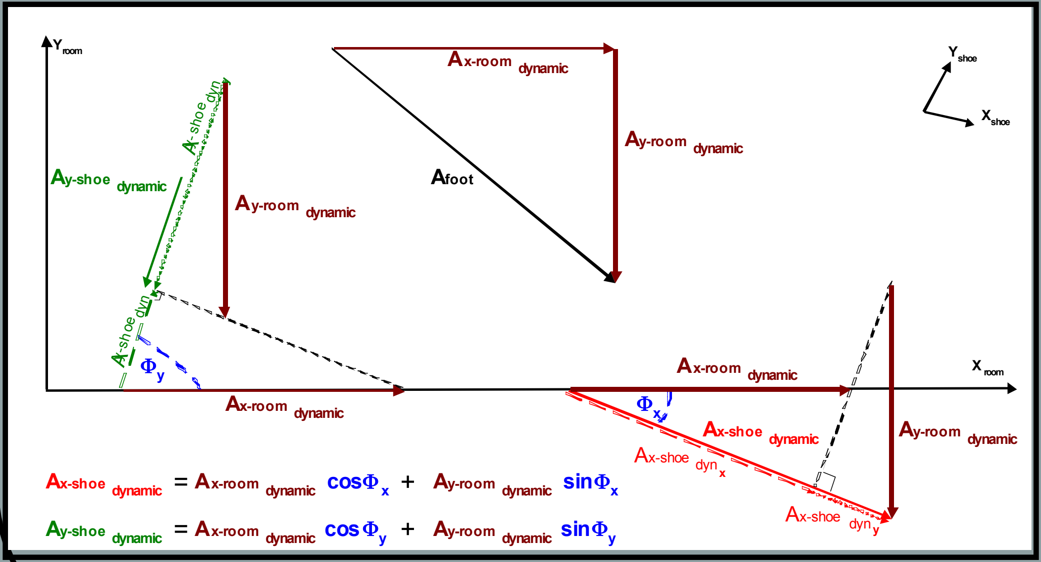


Recommendation: Consider replacing Murata Gyroscopes with Analog Devices Gyroscopes

Stride Length: Accelerometers

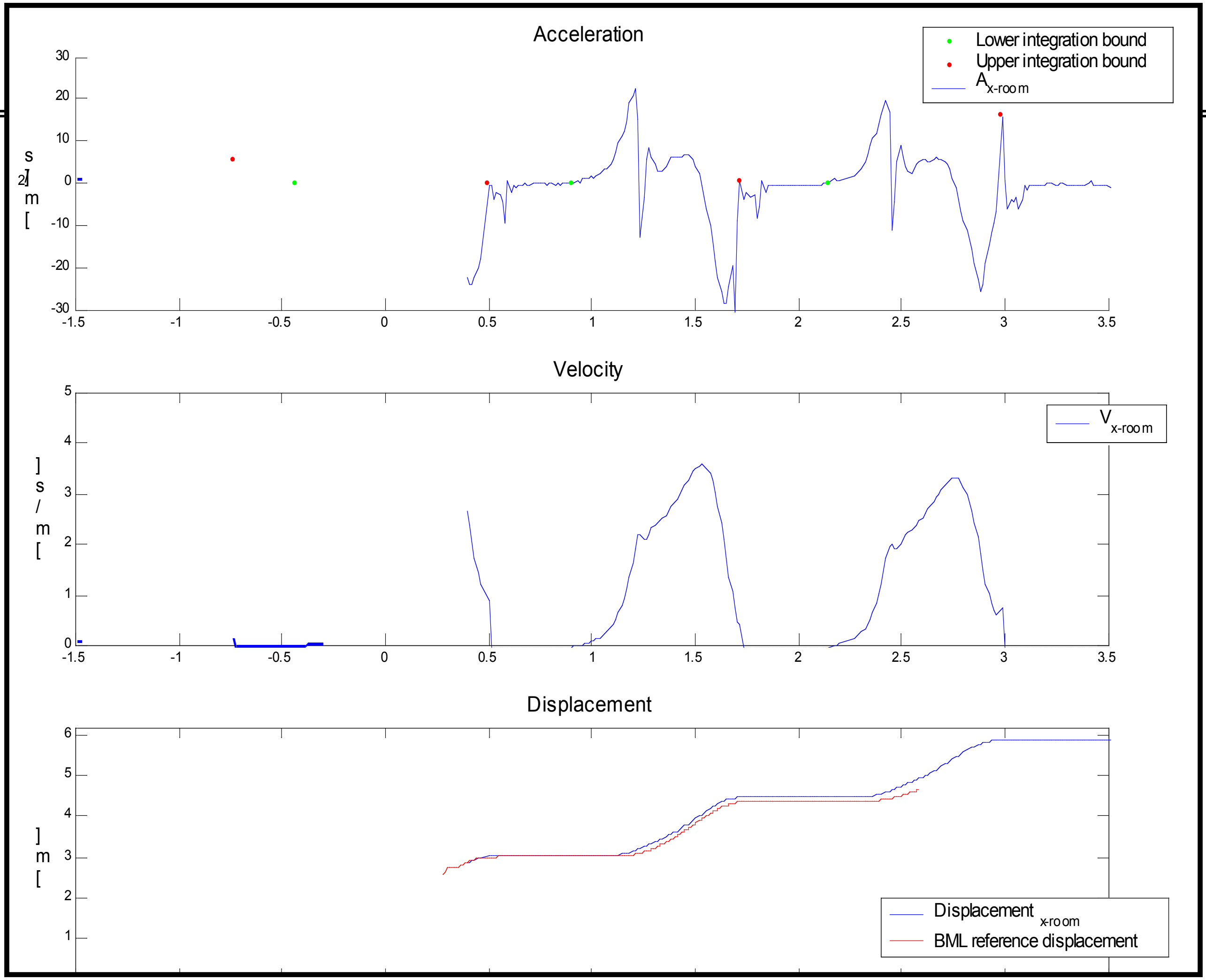
Accelerometers measure dynamic and static acceleration; *pitch* used to subtract static component of gravitational acceleration.





X- and Y- accelerometer outputs can be combined to determine acceleration in room coordinates (also requires *pitch*).

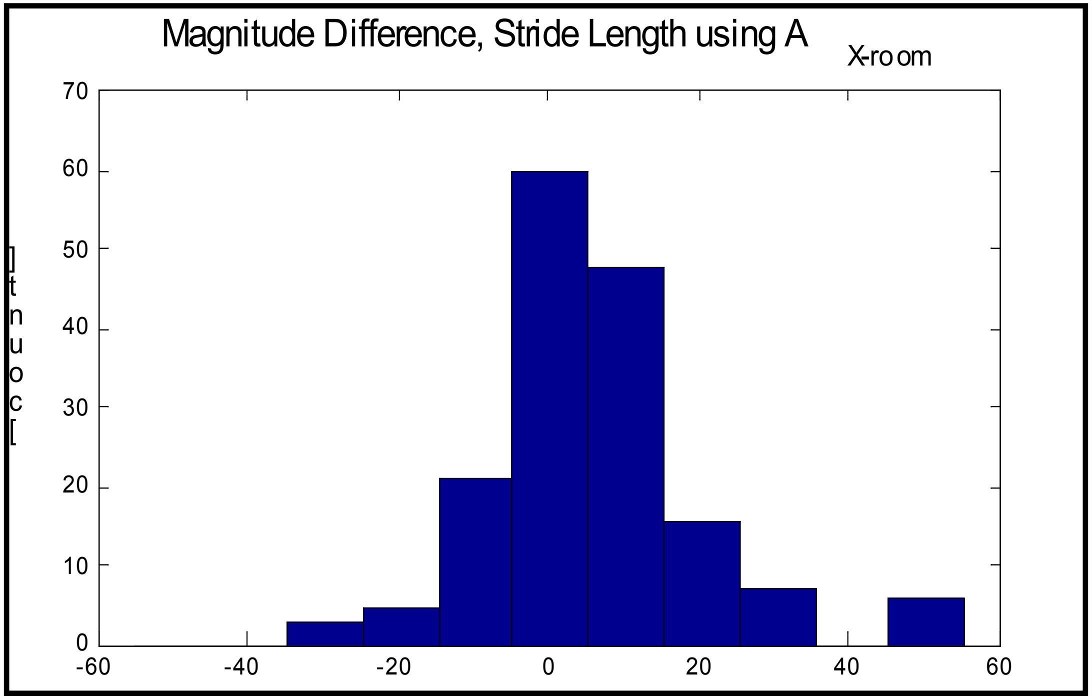
Stride Length



Dynamic component along room x-axis integrated twice with respect to time, over a single leg swing.

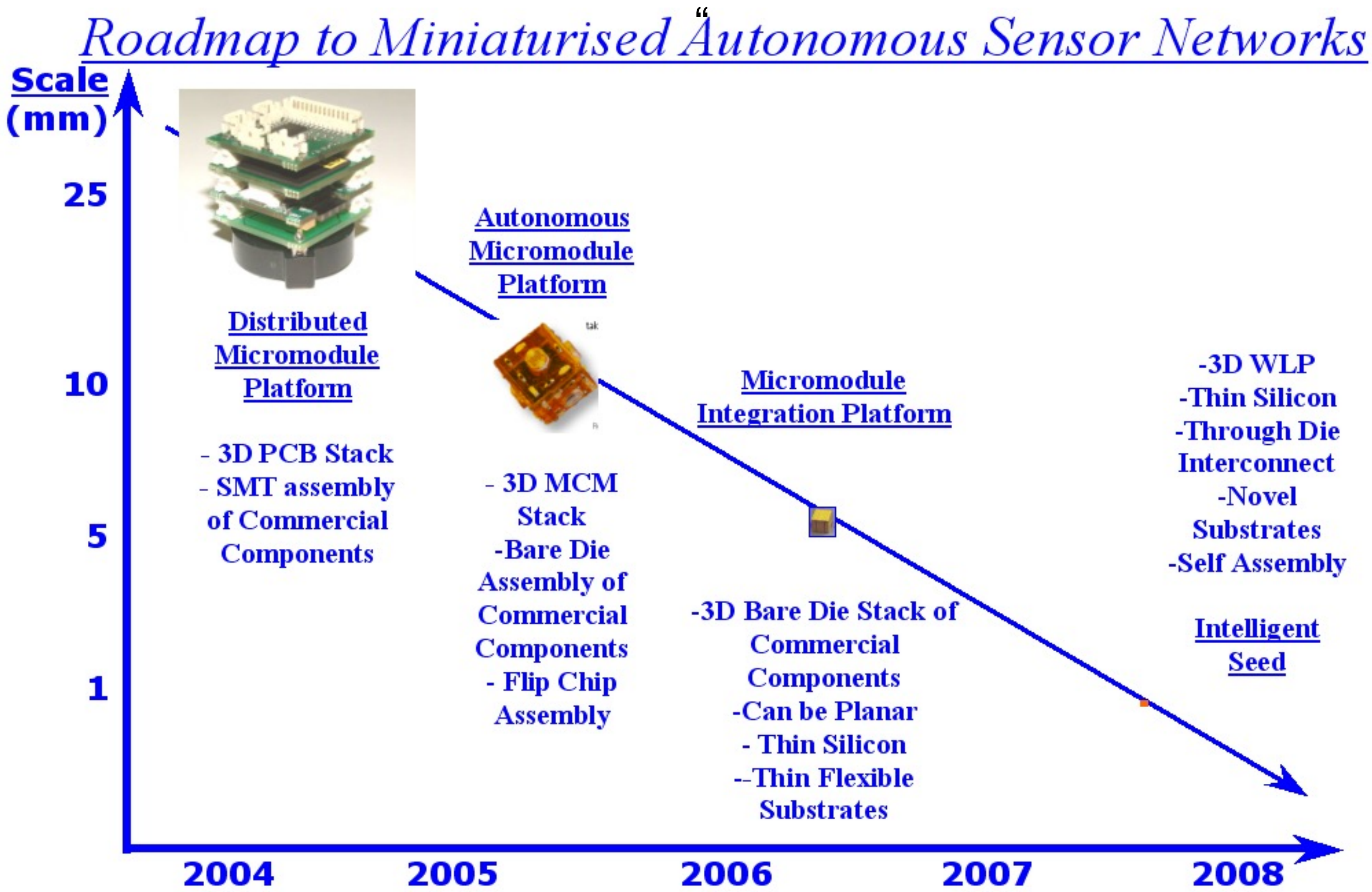
Stride Length Results

Comparison (All GaitShoe minus BML)	Difference		Percent Change		Samples
	Mean	Std Dev	Mean	Std Dev	
Stride Length *Double linear integration of $Ax\text{-}room_{dynamic}$*	6.1 cm	15.4 cm	5.4%	12.9%	166



Recommendation: Improve pitch, incorporate all IMU outputs, Kalman filter

AES Roadmap



Tyndall National Institute

Small Packages…
Barton et al (Tyndall Institute), IPSN 05

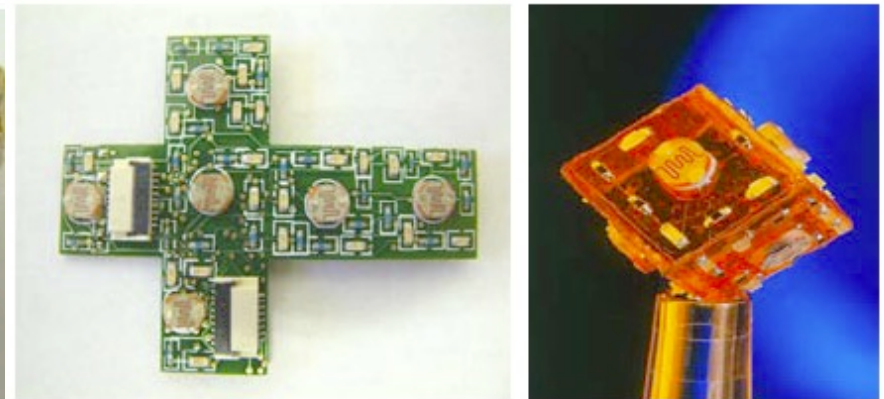


Figure 11. 10mm module development

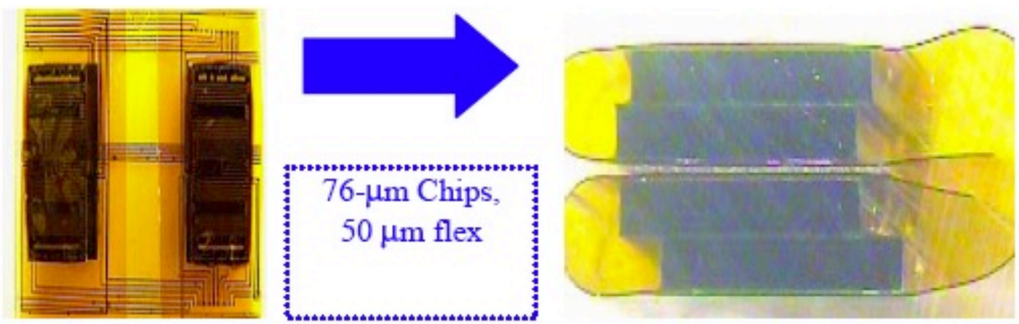


Figure 1. 25mm RF Transceiver Layer, 10mm and 5mm cube form factor development programs

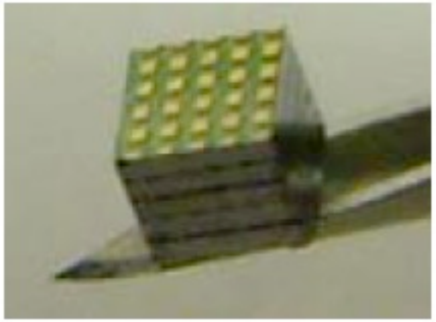
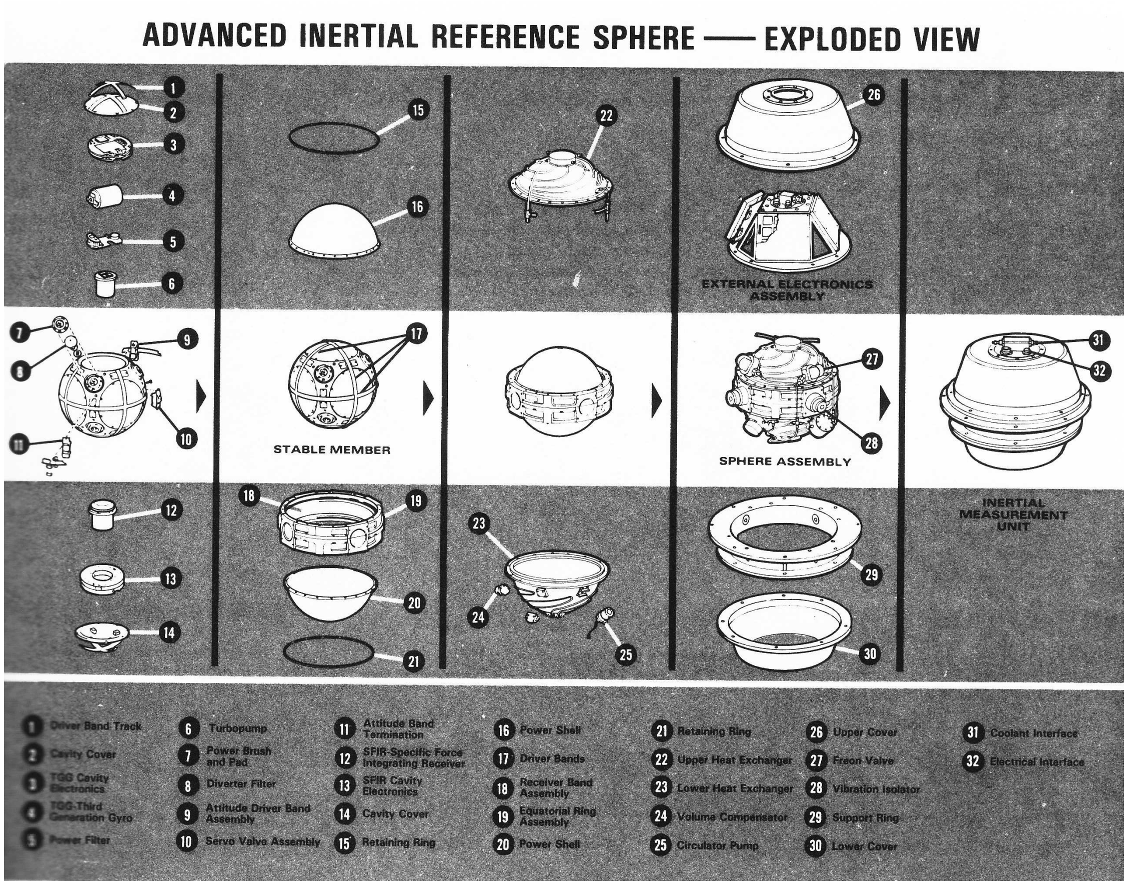


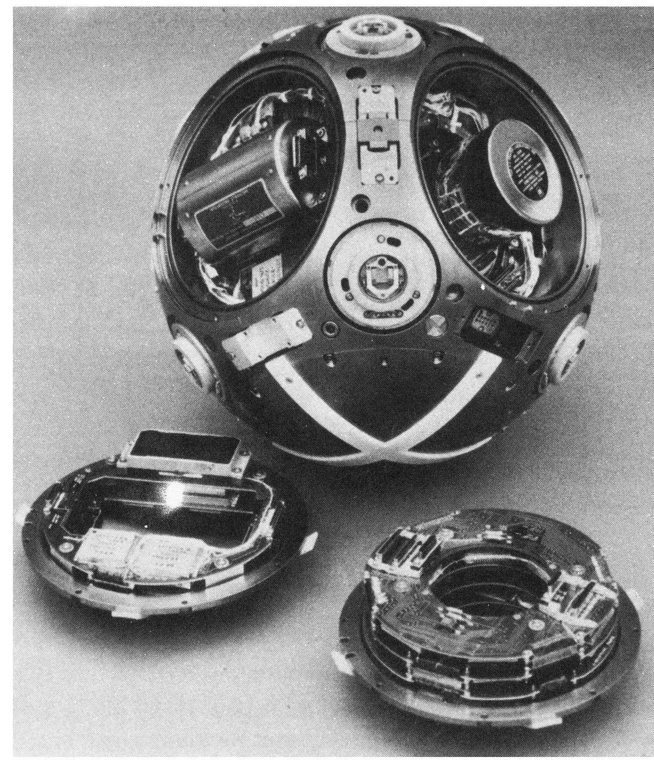
Figure 13. I-seed 1mm³ sensor module development

What if Money is no Object? (1)

- The state of the art in IMU design is the system used in the MX missile, known as the Advanced Inertial Reference System (AIRS).
- Uses the best accelerometers and gyroscopes available (strangely, from 1986)
- The two part spherical structure is gimballed by floating the outer sphere in fluorocarbon fluid and maintaining the orientation of the inner sphere via hydraulic thrust valves.
- Circular error probable (CEP) of 100m
  - Will fall within that range 50% of the time.

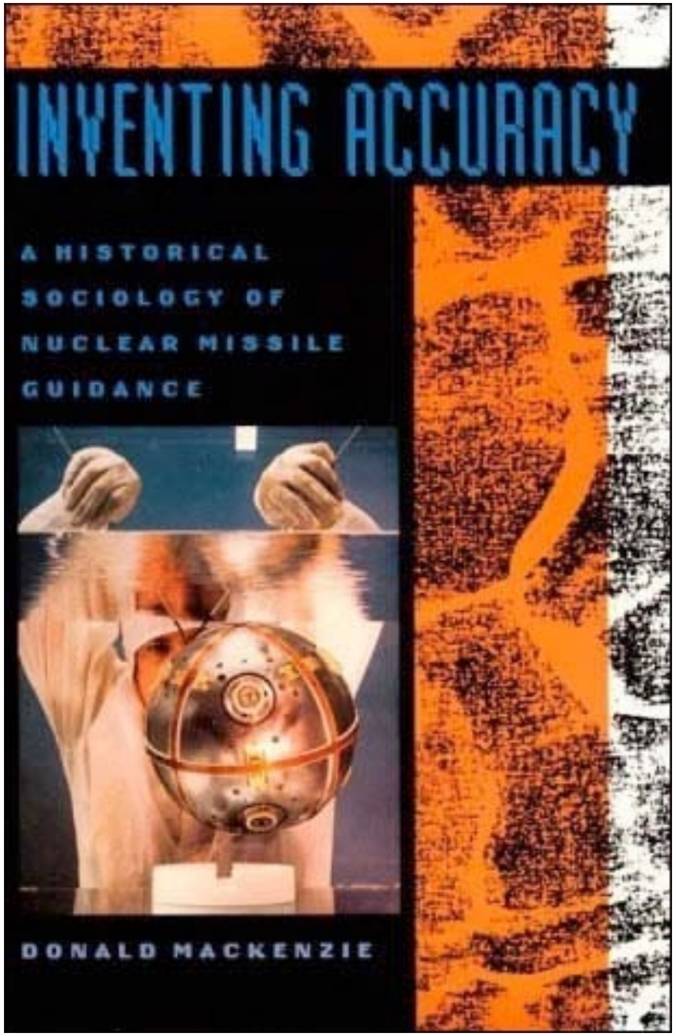
What if Money is no Object? (2)





Ask Joe what he did as a UROP!

Mackenzie’s book tells the story!



MIT Press