Inertial Measurement for planetary exploration: Accelerometers and Gyros

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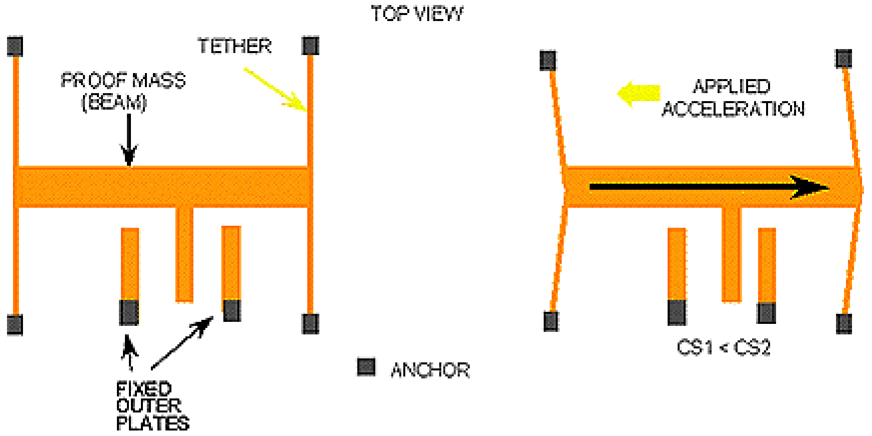
Significance of Inertial Measurement

- Important to know “where am I?” if you’re an exploration robot
- Probably don’t have access to GPS or road signs to help you
- Mass (inertia) is a property that holds regardless of environment (gravity or no)
  - Want to harness this for internal estimation of state (position and velocity)

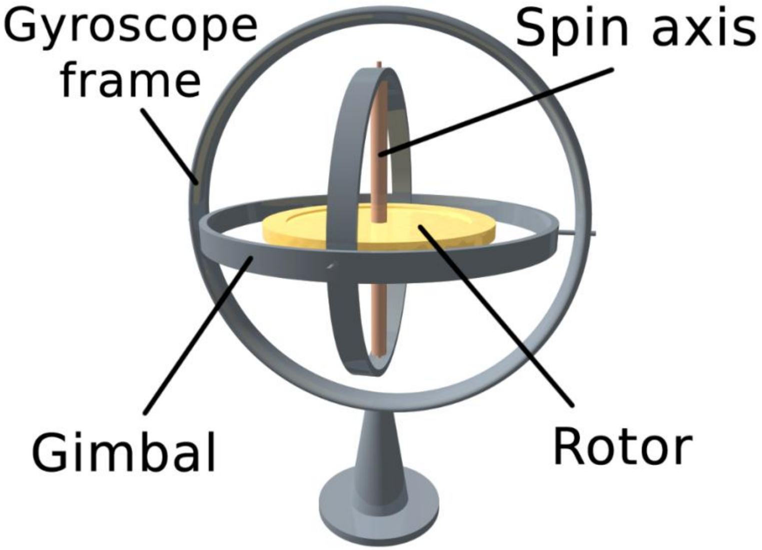
Physics and mechanical fundamentals: Accelerometers

- Newton's 3rd law F = ma --> F/m = a
  - Measure deflection of a proof mass: Δx
  - Known compliance of spring or cantilever beam gives you force: F = k Δx
- Principles of transduction
  - Measure deflection via piezoelectric, piezoresistive, capacitive, thermal
- Device types
  - Macro-sized (old-school)
  - MEMS: beam micro-machined from silicon wafer
  - Single- or multi-axis



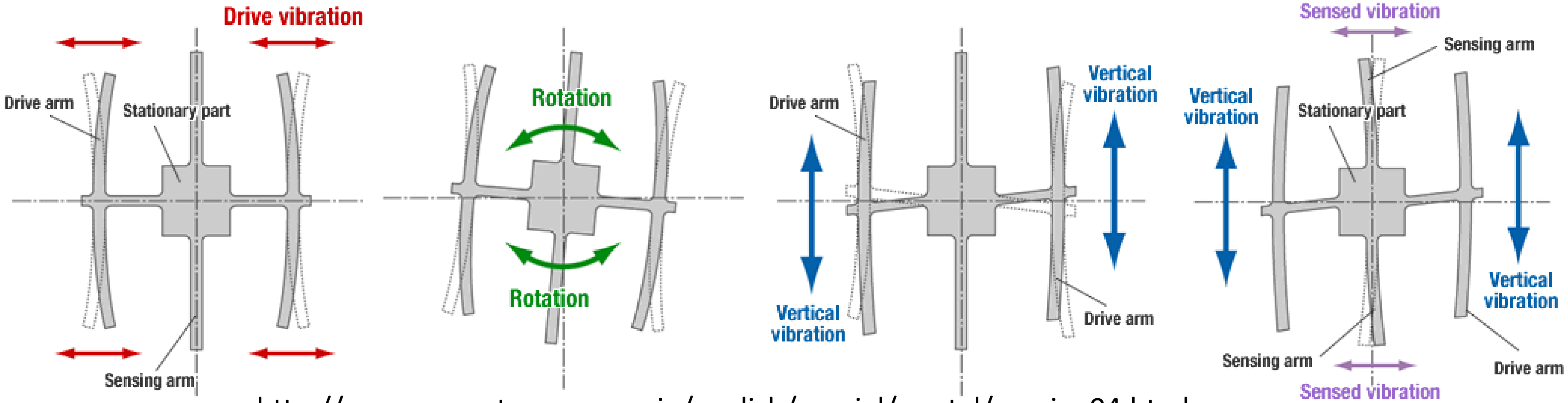
Physics and mechanical fundamentals: Gyroscopes

- Precession: angular momentum conservation
  - Torque on spinning body results in torque about a 3rd axis
  - Precession torque generates signal to gimbal servos
  - Transduction: Magnetic induction "pick-offs" to determine angles between gimbal frames



Physics and mechanical fundamentals: Gyroscopes

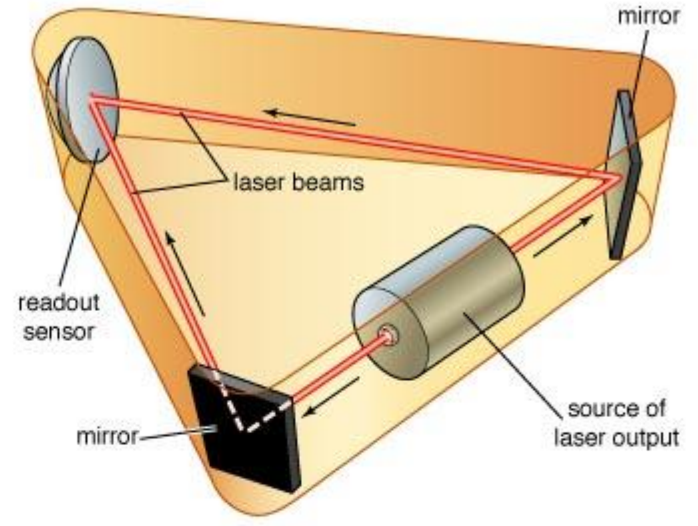
- Coriolis force
  - Oscillating beam experiences in-plane rotation
  - Coriolis force causes perpendicular vibrations
  - Devices: piezoelectric gyro, hemispherical resonator gyro, MEMS gyro



http://www.epsontoyocom.co.jp/english/special/crystal/sensing04.html

Physics and mechanical fundamentals: Gyroscopes

- Light interference
  - Laser light is split to travel opposite directions around a circuit
  - Rotation → path length differences
  - Devices: ring laser gyro (RLG), fiber optic gyro



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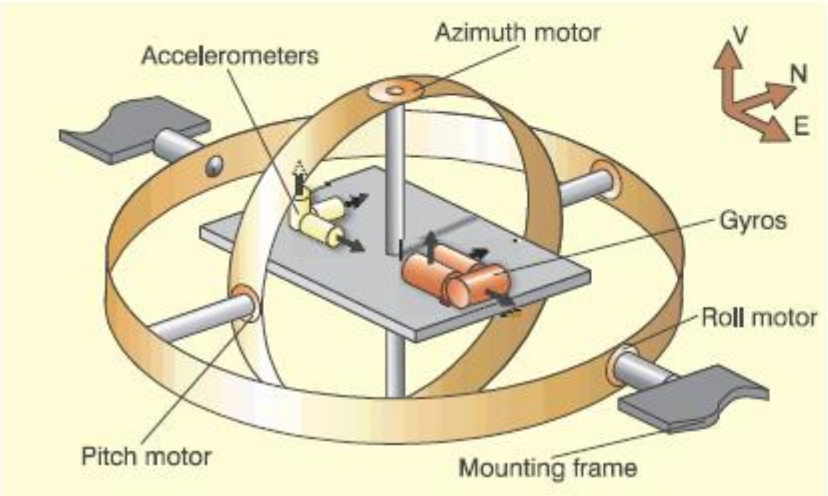
Gimballed or Strapdown?

- <u>Gimballed units</u>
  - Whole IMU mounted in gimbal frame
  - Vehicle orientation measurement is “easy”
  - Problems:
    - Errors grow near “gimbal lock”
    - Weight, power consumption, size, cost

- <u>Strapdown units</u>
  - No gimbals required (no gimbal lock!)
  - Smaller, lighter, can be cheaper
  - Problem:
    - Requires digital computing to accurately track vehicle orientation based on gyro readings



Bring it together: IMU

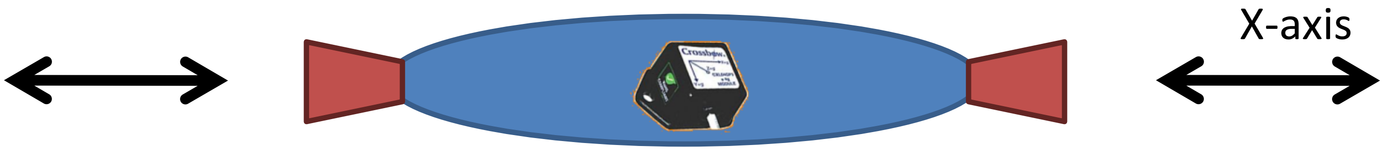
- Sensor fusion
- IMU gives you Δv and Δθ
- Integrate readings (dead reckoning)
- Problems
  - Accumulated error and drift
  - Noise
  - Gimbal lock
  - Changing gravity direction (as traveling over surface of a planet – affects accelerometers)
  - Temperature effects
  - Cost of accuracy

Bring it together: IMU

- Solutions
  - Calibration
  - Redundancy and skew (multiple IMUs)
  - Filtering (Kalman, traditional)
  - Schuler tuning (for gravity direction changes)
  - Realignment using visual markers/fixes
  - Combine with other sensors (GPS, compass, airspeed, odometer)
  - Built-in temperature sensor with analog circuitry for correction

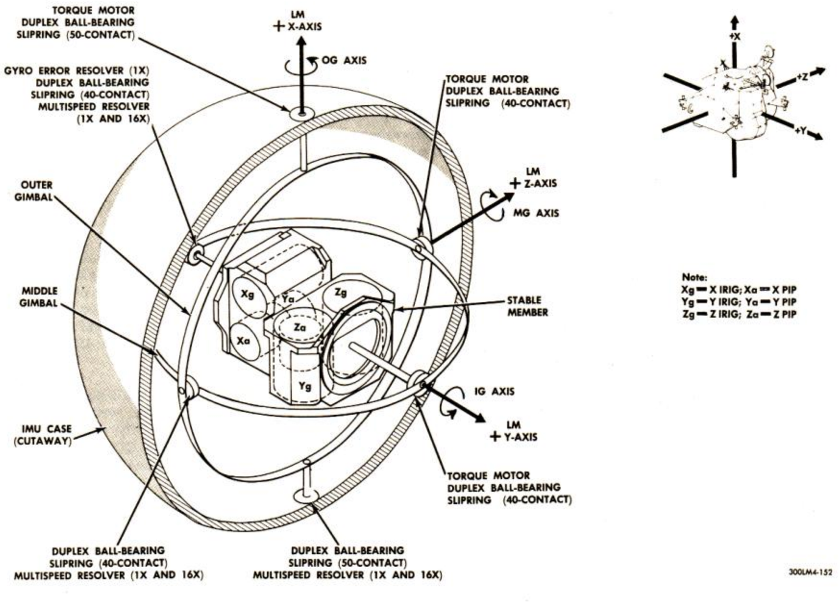
Homework: Underwater robot position estimation

- We have a submersible robot with uni-directional thrusters at each end (rear and aft) and a 3-axis strap-on accelerometer (**Crossbow CXL04GP3 –** look up the specs here: www.xbow.com) mounted inside
- It is executing a 30 sec. maneuver in a straight line using it's thrusters
- I'm providing you with the x-axis (aligned with direction of motion) voltage signal collected by the DAQ system for duration of the maneuver (collected at 100 Hz using a 16-bit analog-digital converter)
    1. Integrate the signal (you need to convert it from volts back to m/s^2) to get an estimate of the robot's position at the end of the 30-second maneuver. You may assume the accelerometer was properly calibrated and the robot starts from rest.
    2. Given the noise in the signal (it's uniform noise sampled within +/- the stated RMS noise range of the sensor), what is the uncertainty of your final position estimate?
    3. Now imagine the robot executes the same maneuver in much colder water without re-calibrating the accel. first. Assume the zero-point of the accel. has drifted so that it now outputs 2.4 V at 0 g. Repeat Question 1 using the new zero-point. How does the accelerometer drift affect your position estimate? Comment (qualitatively) on the consequences of uncorrected accelerometer drift on the accuracy of your estimate.



Historical applications

- Originally developed for rockets/missiles (Robert H. Goddard)
- Apollo missions used IMU with rotor gyros
  - Only used IMU for accelerated phases of mission
  - Align against stars during “coasting” phases
  - Star alignment allows for resetting of IMU and repositioning of gyro gimbal axes
  - Gyro errors build up quickly near gimbal lock
- MUST AVOID GIMBAL LOCK



Note:
Xg — X IRIG; Xa — X PIP
Yg — Y IRIG; Ya — Y PIP
Zg — Z IRIG; Za — Z PIP

Figure 2.1-24. IMU Gimbal Assembly

Application: NASA Shuttles

- Shuttles outfitted with 3 High Accuracy Inertial Navigation Systems (HAINS) from Kearfott Corp.
  - Redundant IMUs mounted at varied angles (skewed)
- IMU contains rotor gyro on 4-gimbal frame and 3 accelerometers
  - 4 gimbals avoids gimbal lock
- Alignment updates obtained from on-board star trackers

Application: Mars Exploration Rovers (MERs)

- MERs landed with two LN-200S units from Northrup Grumman
- IMU contains 3 fiber optic gyros and 3 MEMS accelerometers
- Experiences temperatures cycles -40 to 40 ˚C

LN-200S IMU
Weight: 1.65 lb
Size: 3.5” dia x 3.35” h
Operating range:
    Angular rate: ±11,459 deg/sec
    Angular accel: ±100,000 deg/sec^2
    Accel: 70 g

Other Applications

- Aircraft navigation
- Tactical missiles and smart munitions
- Submarine/naval navigation
- Spacecraft
- Land travel (cars, robots, tractors)

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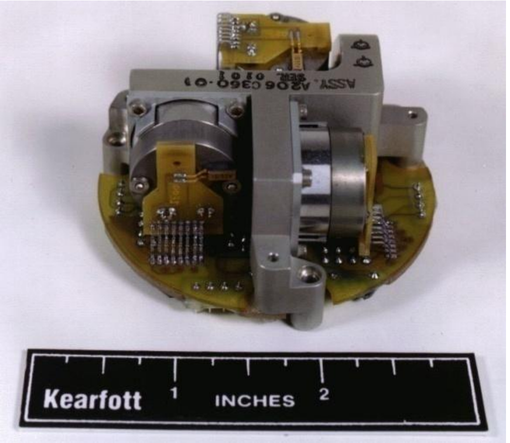
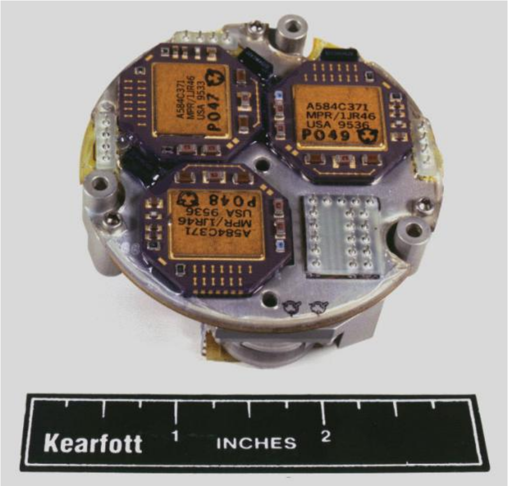
Companies that make IMUs

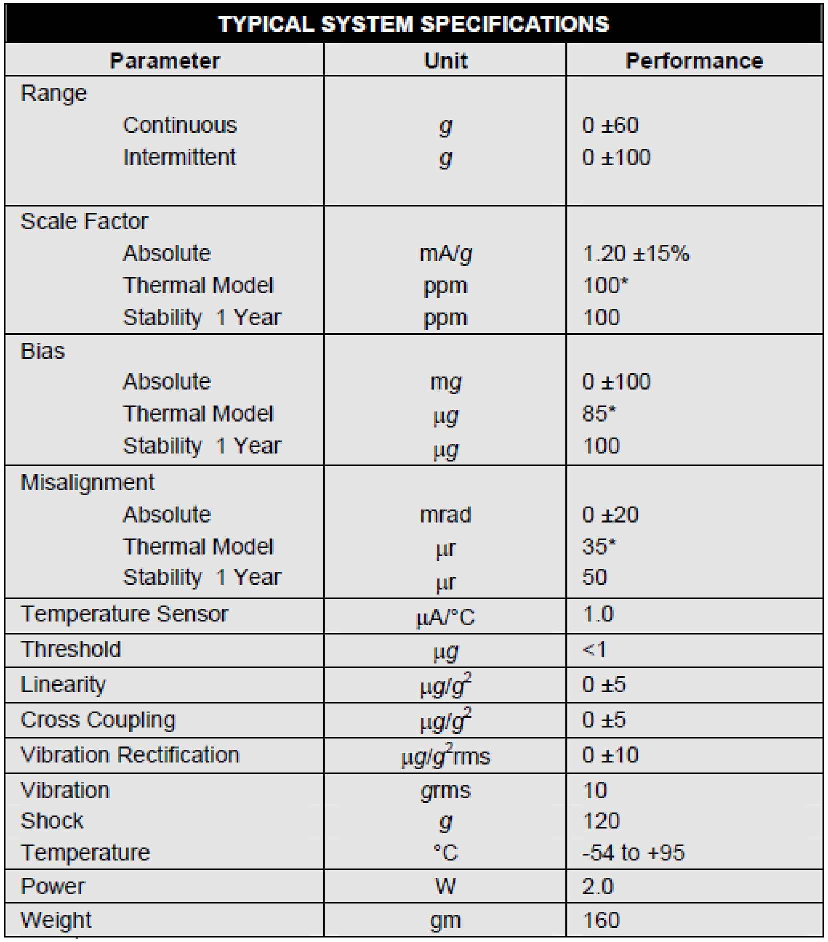
- Military/Government Contractors
  - Honeywell (UAVs, missiles)
  - Northrup Grumman (MERs)
  - BAE (missiles)
  - Kearfott Corporation (NASA shuttles)
- Civilian Applications
  - Crossbow
  - Analog Devices

Example: Kearfott MOD VII Accelerometer triad assembly

- 3 pendulum accelerometers (for 3-axis measurements)
- Capacitive position detection
- Old design (around for 40 years)







TYPICAL SYSTEM SPECIFICATIONS

Parameter	Unit	Performance
Range		
Continuous	g	0 ±60
Intermittent	g	0 ±100
Scale Factor		
Absolute	mA/g	1.20 ±15%
Thermal Model	ppm	100*
Stability 1 Year	ppm	100
Bias		
Absolute	mg	0 ±100
Thermal Model	μg	85*
Stability 1 Year	μg	100
Misalignment		
Absolute	mrad	0 ±20
Thermal Model	μr	35*
Stability 1 Year	μr	50
Temperature Sensor	μA/°C	1.0
Threshold	μg	<1
Linearity	μg/g^2	0 ±5
Cross Coupling	μg/g^2	0 ±5
Vibration Rectification	μg/g^2rms	0 ±10
Vibration	grms	10
Shock	g	120
Temperature	°C	-54 to +95
Power	W	2.0
Weight	gm	160

Example: Crossbow GP-series MEMS accelerometer

- 3-axis MEMS accelerometer
- Light weight, small
- Cheap: ~$150

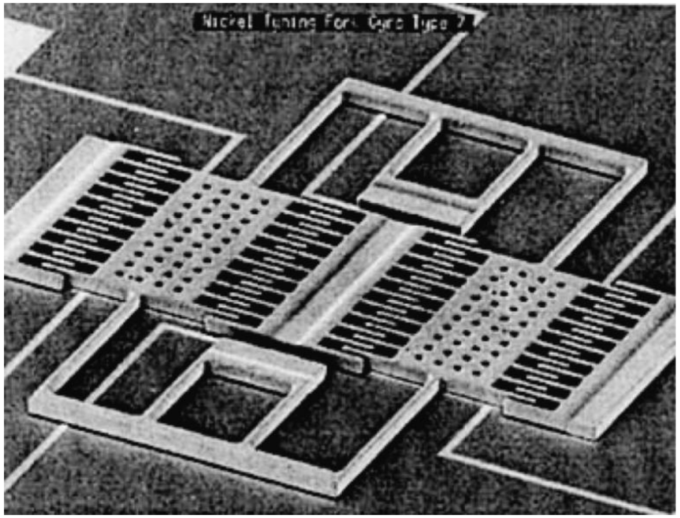
CXL04GP3
Range: ± 4 g
Bias: ± 0.1 g
Noise: 10 mg (rms)
Bandwidth: 100 Hz
Operating temp: -40 to +85
Shock: 2000 g
Weight: 46 grams

IMU Comparisons

	Crossbow IMU320	Crossbow IMU700CB-200	Northrup Grumman LN-200
Gyros: Type	MEMS	Fiber-optic	Fiber-optic
Range	± 150 °/sec	± 200 °/sec	± 11,459 °/sec
Bias (in-run)	< 30 °/hr	< 20 °/hr	< 10 °/hr
Random walk	3 °/sq-rt hr	0.4 °/sq-rt hr	<0.15 °/sq-rt hr
Bandwidth	20 Hz	100 Hz	
Accelerometers: Type	MEMS	MEMS	MEMS
Range	± 4 g	± 4 g	± 70 g
Bias (in-run)	< 0.5 mg	< 12 mg	< 3 mg
Bandwidth	20 Hz	75 Hz	
Whole Unit: Cost	~ $1,000	~ $3,000	~ $50,000 ???
Size, weight	10.8 x 8.9 x 3.8 cm, < 0.45 kg	12.7 x 15.2 x 10.1 cm, < 1.6 kg	8.9 dia x 8.5 h cm, <0.75 kg
Temp range	-40 to +85 °C	-40 to +60 °C	-54 to 71 °C
Shock		100 g (non-operating)	90 g

Advancing the art…

- Smaller, cheaper, faster computers for on-board computation
- Advances in silicon manufacturing technology, MEMS
- Improving MEMS accuracy
- Integration of MEMS inertial sensors with CMOS chips



Institutions and labs on cutting edge

- MEMS research still ongoing, but accel. and gyro research is old news
  - CMU's own MEMS lab involved in MEMS/single chip integration (circa. 2003)
- Aerospace companies seem to be leading advances in extremely accurate IMU's
- MEMS labs developing small/cheap integrated IMU's

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