Inertial sensors

- INS = Inertial Navigation System
- IMU = Inertial Measurement Unit
- Gyros and acceleration sensors
- Based on conservation of momentum/inertia or changes of the path length (optical gyros)
- → no external support needed, work everywhere under the known physical laws

Gyroscopes

- Non-sensitive to magnetic disturbances
- => can be used also in environment where the magnetic field is not available
  - Mechanical gyroscopes
    - based on conservation of momentum
    - Measure the changes in linear- or angular momentum
  - Optical gyroscopes
    - no moving parts $\Rightarrow$
      - Service free
      - gravitation doesn't affect

        $\Rightarrow$ no need for gimbal mounting

Gyroscopes

- There are two basic classes of rotation sensing gyros:
  - Rate gyros
    - the output is relative to the angular speed
  - Rate integrating gyros
    - Indicate the actual turn angle or heading
    - The angle is relative => must be initiallly referenced to a known orientation
    - Angle is anyway integrated from angular speed → the primary measuring magnitutude of a gyro is always angular speed!!

Gyro performance

- Classification according to bias drift
- Rate grade 10 – 10000 deg/h
- Tactical grade 0,01 – 10 deg/h
- Navigation grade <0,01 deg/h
- Mechanical, optical (fog, laser ring), **MEMS** (tuning fork, vibrating ring)
- Dynamic area: few Hz – 500Hz

Gyro parameters

Check these always!

- Drift (see previous slide) [deg/h]
- Max angular speed [deg/s]
- Dynamic resolution [Hz]

- Not always easy!

Mechanical Gyroscopes

- Based on conservation of momentum
  - Continuous angular movement
    - Mm. flywheel gyroscope
  - Oscillatory angular momentum
    - Employ a torsionally suspended mass oscillating back and forth at its natural frequency
  - Continuous linear momentum
    - Steady stream of fluid, plasma or electrons, which tend to maintain its established velocity
  - Oscillatory linear momentum
    - a set of discret masses moving back and forth along a straight-line path (* or ⇔) (tuning-fork rate gyro)
  - In robotics most relevant are optical and MEMS

Mechanical Flywheel Gyroscope

- A rapidly spinning wheel or sphere with big inertia causes a gyroscopic presession, when turned
- Rotor is rotated with electrical motor
- Rotor on supported by low-friction bearings and mounted in a gimbal
- Both axis of the gimbal are perpendicular to the rotating axis

The rate of precession Ω is proportional to the torque T applied to the rotating mass:

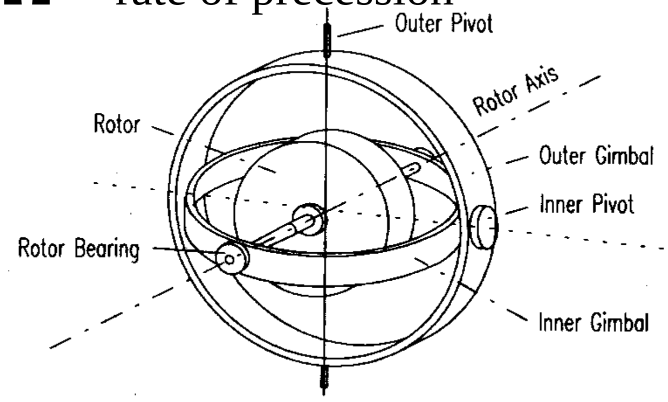
$\boldsymbol{T} = \boldsymbol{I}\omega\Omega$, where

$\boldsymbol{T}$ = applied input torque

$\boldsymbol{I}$ = rotational inertia of rotor

ω = rotor spin rate

Ω = rate of precession



Gyrocompass

- special configuration of the rate integrating flywheel gyroscope
- If spinning axis is along the meridian (north-south) no tilting (precession) occurs => if tilting occurs the axis is no more along the meridian
- By adding a weight as gravity reference a two axis gyroscope will become a north-seeking instrument
- The function is dependent upon four principles:
  - Gyroscopic inertia
  - Gyroscopic presession
  - Earth’s rotation
  - Earth’s gravitational pull
- Not suitable for robots (size, weight, price, initialization time, shock and vibration sensitivitiness, power consumption etc.)

Gyro compasses

Brown Gyro-compass
1914, 12000 rpm

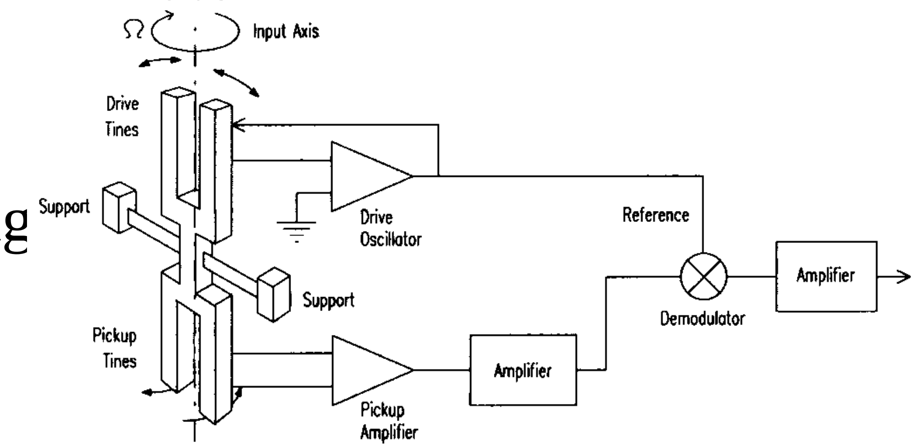
Sperry MkE-1 Gyro
Compass 1954

Tuning-fork Gyro

- Mechanical tuning-fork gyro is one of the most popular and low-cost gyroscopes in land-based mobile applications
  - Simple
  - Reliable
- The tines of a tuning-fork are oscillating towards and away from one another (magnetic coils, piezoelectric oscillator)
- Any rotation of the gyro assembly about the vertical axis caused induced Coriolis forces acting on the tines (in horizontal plane) => this torsional vibration is proportional to the rate of turn
- Possible vibrational elements: strings, triangular and rectangular bars, cylinders and hemispheres

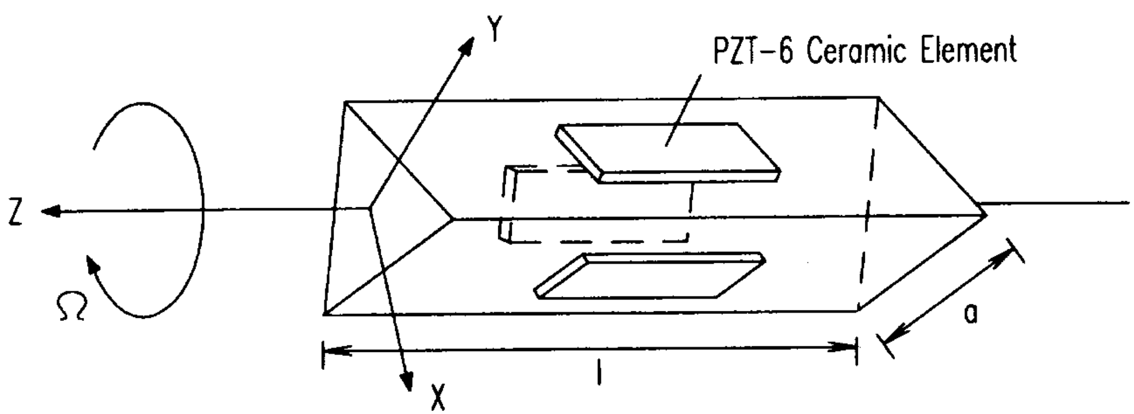
Systron Donner GyroChip

- Tuning-fork and support structure chemically etched from a single wafer of Piezoelectric quartz
- upper (drive) tines are actively driven by an oscillator towards and away from one another ⇒ each tine will experience a Coriolis force when fork is rotated
- Coriolis forces cause a vibrating torsional torque
- Pick-up tines react to the vibrating torsional torque
- The vibration signal of pick-up tines is demodulated into a DC signal, which is proportional to the rotation rate



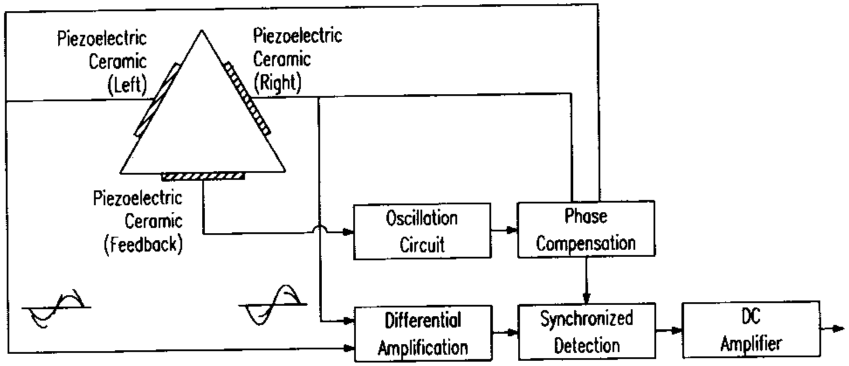
Murata Gyrostar

- One axix piezoelectric rate gyro
- Ceramic elements symmetrically on a triangular metal bar
- bar is made to vibrate in the X-direction at its natural frequency
- the rotation around Z-axis introduces a Coriolis force that causes a vibration in Y-direction at the same frequency
- Rotation rate is proportional to the amplitude of the induced vibration in Y-direction



Murata Gyrostar

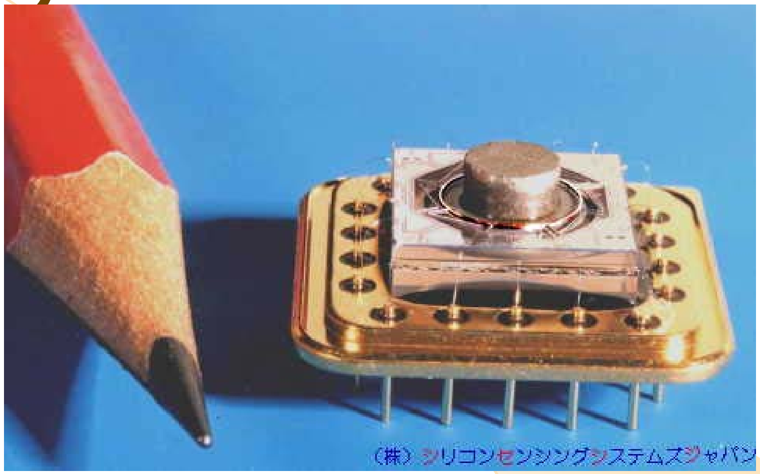
- Triangular bar is made to vibrate with piezo-electric elements on right and left
- the third element is a feedback for the oscillator circuit
- the same drive elements measure the induced Coriolis-force



- Rotation rate is the difference between the drive elements
- For robotics
  - power consuption, size, price => one of the most used components
  - drift (temperature,magnetic)

MEMS Gyros

- Tactical grade available
- Japan, USA
- Best in silicon 0.1 deg/h proto
- Further improvements expected
- Also optical MEMS under development

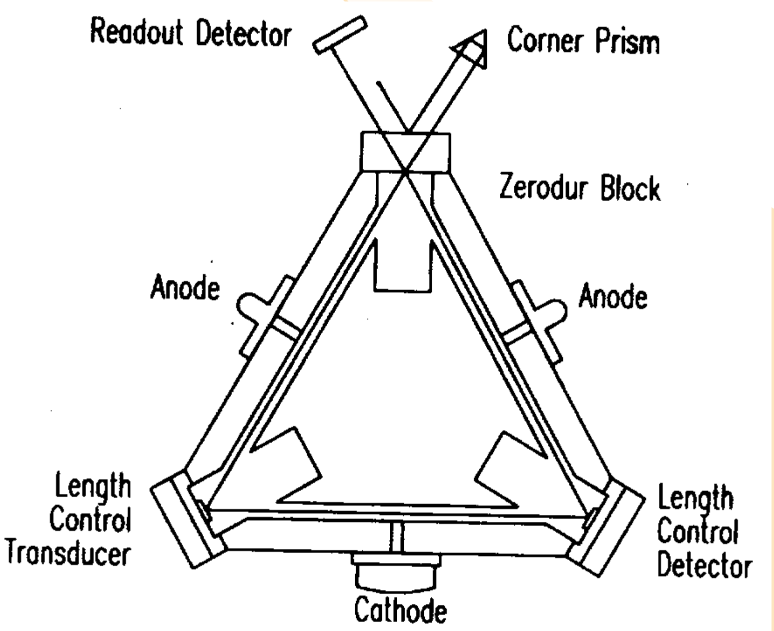


Optical Gyroscopes

- Most promising sensors in the mobile robotics in near future
- two laser beams are rotating opposite directions in a closed loop
- when the beams are combined the rotation rate and direction can be calculated from the interference fringes
- Five basic principles:
  - Active optical resonator
  - Passive optical resonator
  - Open loop fibre optic interferometer (anal.)
  - Closed loop fibre optic interferometer (digit.)
  - Fibre optic resonator

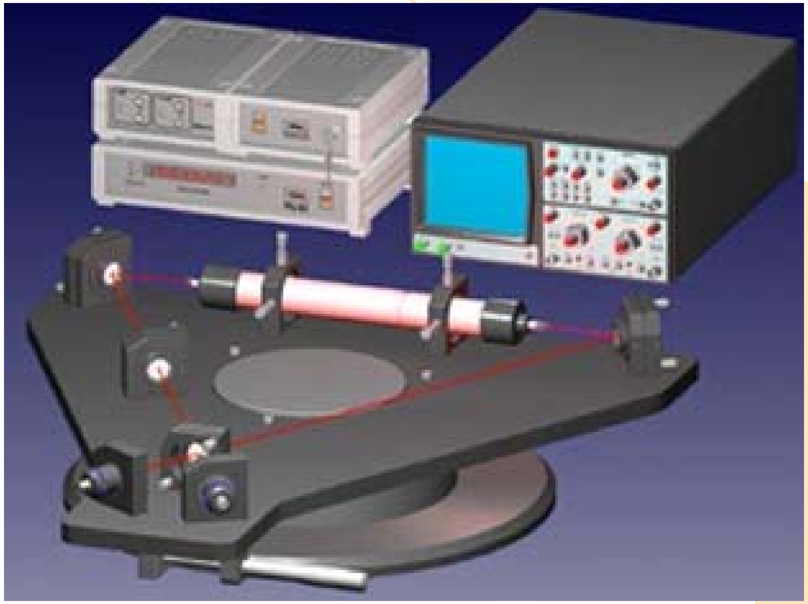
Active Ring-laser Gyro

- Active optical resonator
- Resonator is a laser itself (active)
- If gyro is rotated counter-clock wise direction, the counter-clock wise beam is travelling slightly longer than the opposite beam
- The change in the path length is proportional to the rotation rate
- In very small rotation rates there is a dead-band because of *frequency lock-in*



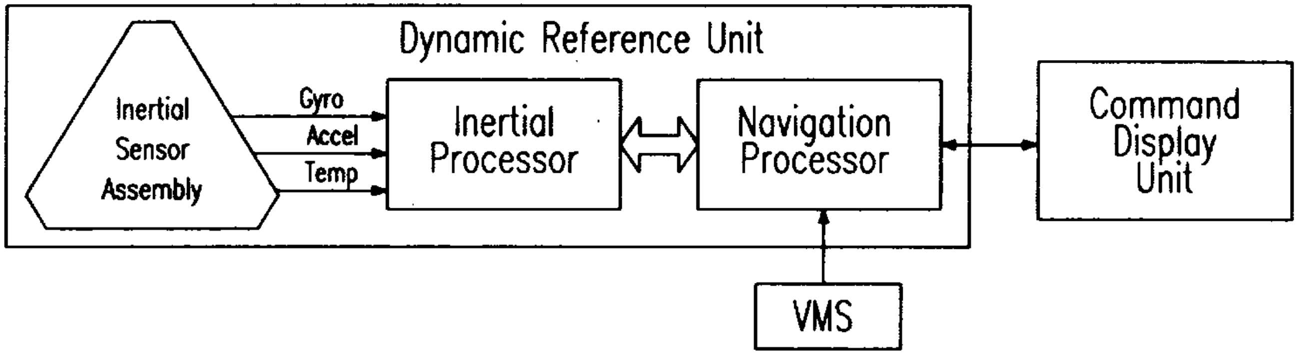
Laser ring gyro

- Laser ring gyroscope
- 0,001 deg/h
- standard, in use!!!
- Suitable for robots except price



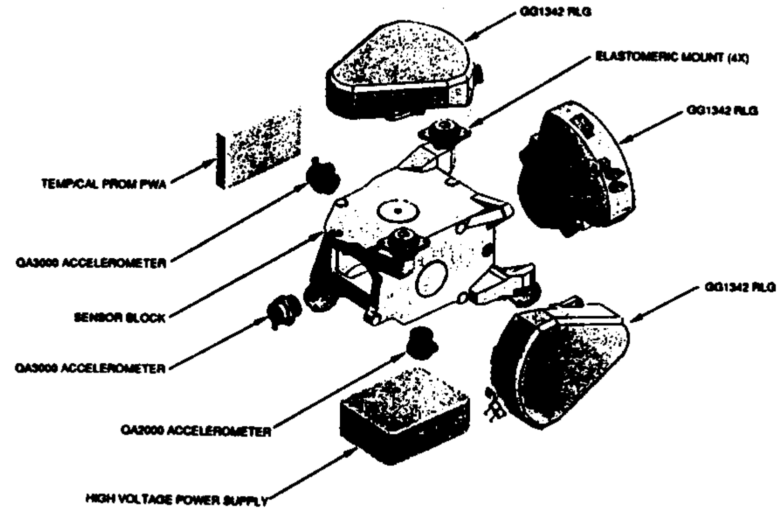
HONEYWELL MAPS

- Modular Azimuth Positioning System (MAPS)
- Complete stand-alone navigation system
- Three sub units:
  - Dynamic Reference Unit (DRU)
    - Inertial Sensor Assembly (ISA)
    - Inertial processor
    - Navigation processor
  - Control and Display Unit (CDU)
  - Vehicle motion sensor (VMS)



HONEYWELL MAPS

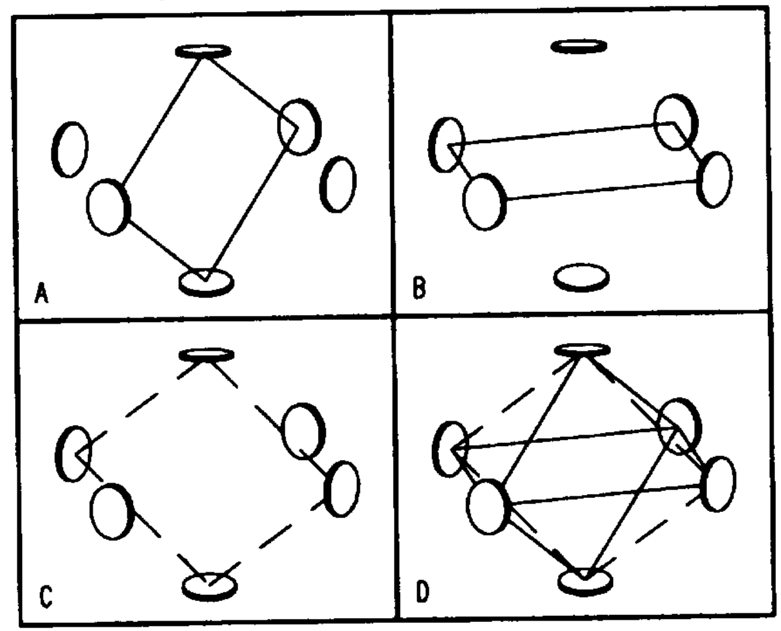
- VMS is optical incremental encoder, which is connected to vehicle's odemeter cable
- Inertial Sensor Assembly has three laser-ring gyroscopes and three acceleration sensors
- Inertial sensor pairs (gyro + acceleration senasor) are located perpendicular to each other



- The initialization of heading is made by measuring the components of earth's rotation from stationary vehicle

Kearfott Gyro

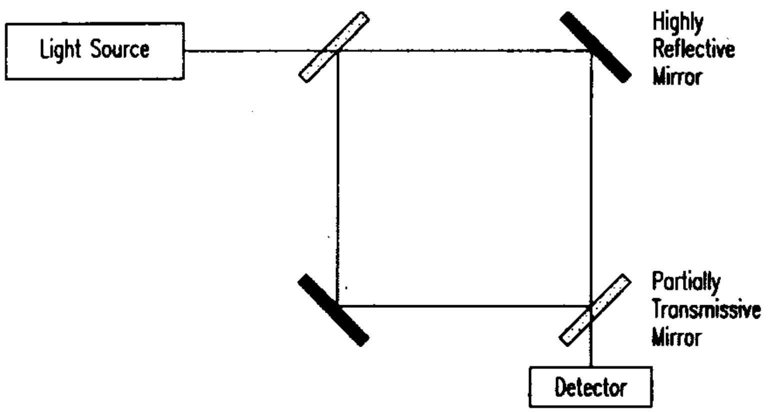
- New design of three axis active optical resonator in order to reduce size
- Six mirrors in the center of cubic faces
- Three mutually orthogonal laser-ring gyros which are using the same mirrors
- Gyros are functionally independent
- The whole structure inside a monolithic class ceramic block



- No cross-talk between the axis was noticed in the tests

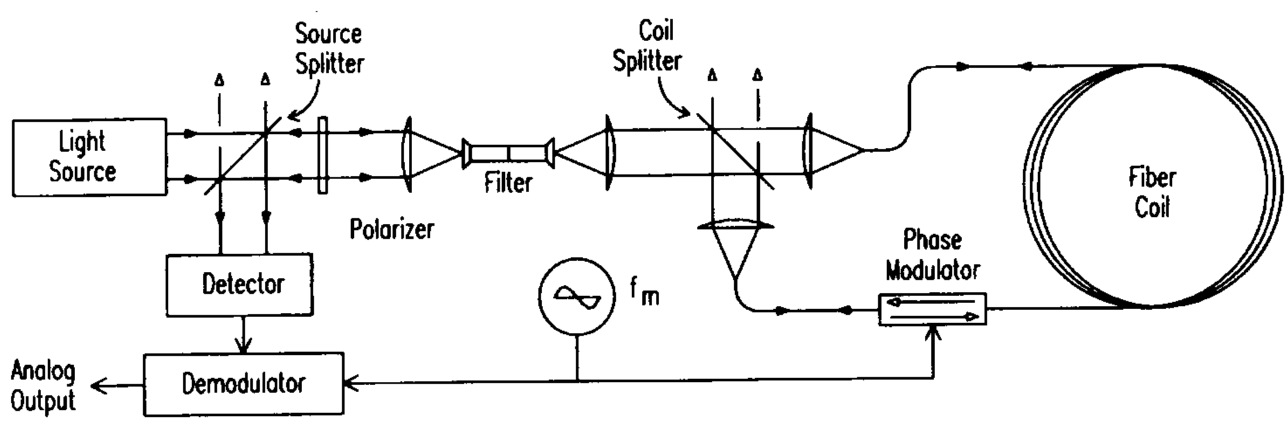
Passive Ring Resonators

- Laser source is outside of the ring cavity ⇒
  - no frequency-lock problem
- The passive structures also eliminates the problems arising from changes in the gain of refraction of the medium
- Changes in the gain change the length of the optical path



Open - Loop Interferometric Fiber - Optic Gyro

- Polarization maintaining single-mode fiber is employed to ensure the two counter-propagating beams in the loop follow identical paths in the absence of rotation
- When gyro is rotated the rate of rotation is proportional to the phase shift between the beams (Sagnac phase shift)



Open - Loop Interferometric Fiber - Optic Gyro

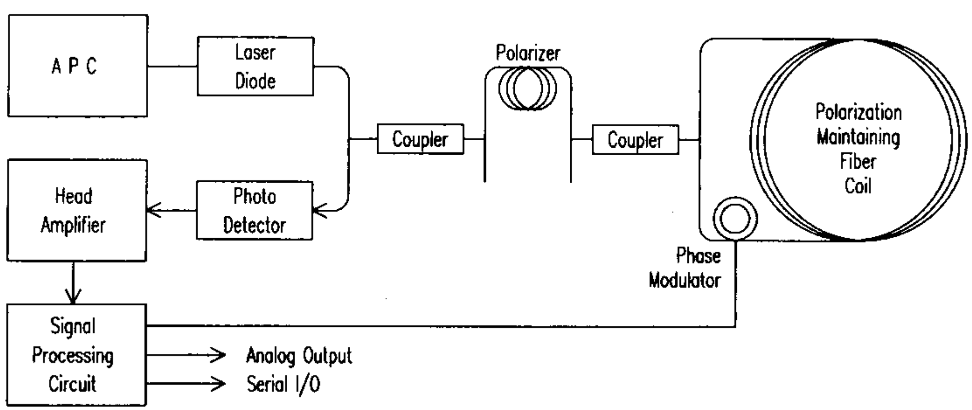
+ low-price
+ not sensitive to shocks and vibrations
+ not sensitive to gravity nor accelerations
+ short initialization time
+ good sensitivity
+ the geometry of the fiber coil is not critical
+ no need to control the length of the optical path

– very long single mode fiber
– the dynamic area is small comparing to ring-laser gyros
– drift caused by the analog components

- Suitable for low-cost applications where best performance is not required
  - Heading of (robots, cars)
  - Tilt and roll sensing

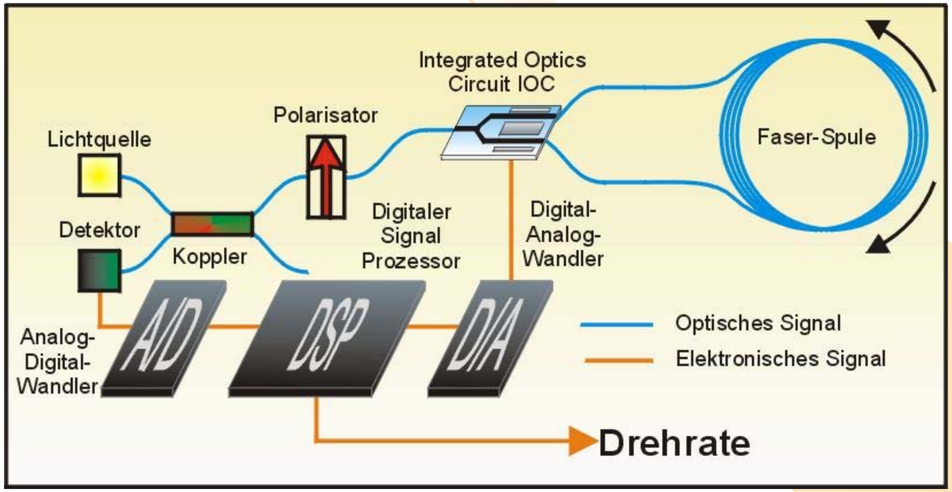
Hitachi Fiber - Optic Gyro

- Hitachi Cable Ltd. is manufacturing one-axis open loop fiber optic gyroscopes
- Hitachi gyros are used in mobile robotics and automotive applications
- Demonstrated Gyro Hitachi FOG-X
- Drift ~ 5 deg/hour



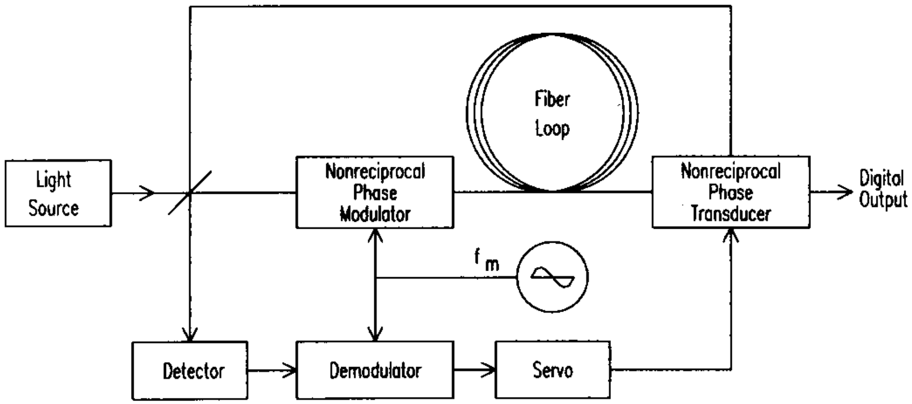
Fibre optic gyro

- Fiber optic gyroscope
- 0,01 deg/h
- Can be produced in a smaller size in principle (looses precision though)
- 3 (or 2) built-in would be very tight.



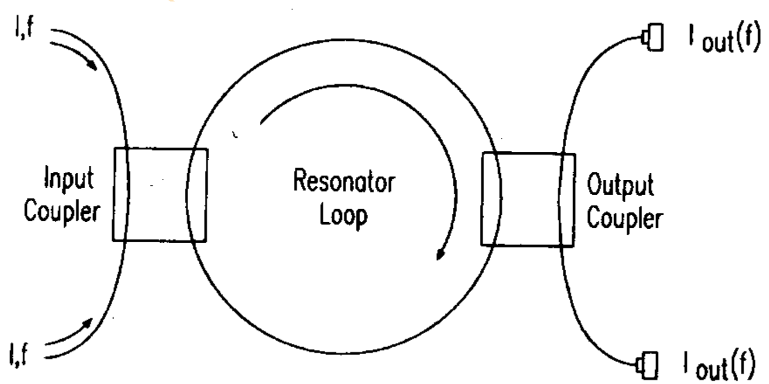
Closed - Loop Interferometric Fiber - Optic Gyro

- For more sophisticated applications like aircraft navigation
- Digital signal processing is more complicated than analog, which is used in open – loop systems
- Benefit comparing to open – loop systems:
  - Not sensitive to light source intensity variations
  - Not sensitive to gains of single components=>very small drift ~ 0,001 – 0,01deg/h
  - Linearity and stability depend only from the phase transducer



Resonant Fiber - Optic Gyros

- Developed from Passive Ring Resonators
- A passive Resonant cavity is formed from multiturn closed loop of optical fiber
- Frequency modulated light is injected from input coupler
- reliable
- Long life
- Short initialization time
- Light
- small amount of fiber



- highly coherent laser source
- extremely low-loss fiber components

Notes

- All mechanical Gyros (mems also) can be affected by external noise like vibrations and magnetic field
- The best bandwith up to 400Hz is available with optical gyros (ring laser) with mechanical ones typically < 10-20Hz
- MEMS and FOGs are the most used in robotics, also in the future

Acceleration Sensors

- **F=ma**
- Moving mass
- capacitive, inductive, resistive
- Integrated Circuit
- Gravity is the problem
- Can be used for gravity sensing as a static position sensor.

ADXL-acceleration sensors

- built on a single monolithic IC
- two capacitor plates series connected form a capacitive divider with the moving center plate which is connected to the moving mass

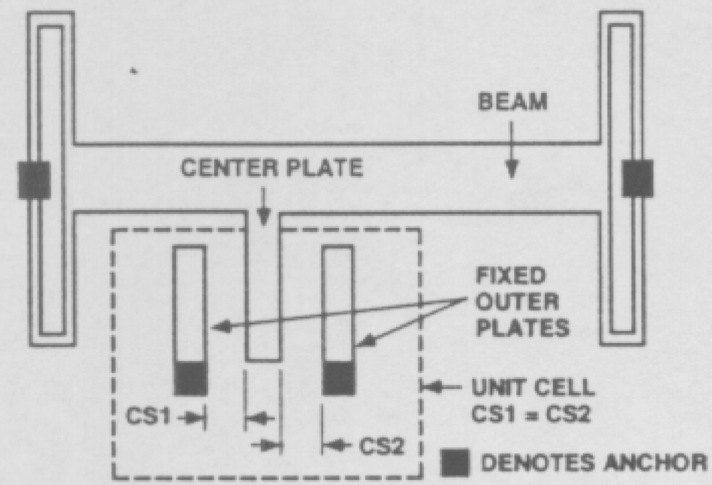


Figure 16. A Simplified Diagram of the ADXL05 Sensor at Rest

ADXL-acceleration sensors

- sensor plates are driven differentially (180 phase shift) by a 1MHz square wave
- when sensor is in rest the centerplate output is zero
- when accelerated the centerplate moves and creates a mismatch between the two capacitances
- output amplitude varies as function of the acceleration

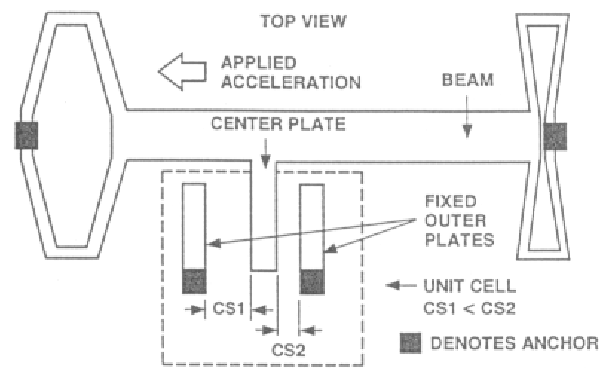


Figure 17. The ADXL05 Sensor Momentarily Responding to an Externally Applied Acceleration

VTI Technologies 3100 family

- ±2 g measurement range (to be extended to cover ±0.5g up to ±6.0g)
- Zero point accuracy over temperature ±70mg to ±100mg
- 3.3V supply
- Offset and sensitivity calibration
- Temperature offset compensation
- Same mechanical design and digital output
- Lead-free Dual Flat Lead (DFL) package:
  - Suitable for lead-free soldering
  - Mounting with normal SMD pick-and-place equipment
  - MSL level 3
- SPI, Digital Serial Peripheral Interface
- Alternate Pulse-Width-Modulation (PWM) output in single axis components
  - Start up and continuous self test,
  - Memory self-test and SPI communication diagnostics

Adopted from: http://www.vti.fi/en/

VTI SCA 3000 three-axis

- Equal performance in all axis (XYZ)
- 2.35 V - 3.6 V supply voltage, 1.7 - 3.6 V digital I/O voltage
- Selectable frequency response
- 64 samples/axis buffer memory for output acceleration data and advanced features enable significant power and resource savings at system level.
- Interrupt signal triggered by motion and free fall
- Size 7x7x1.8 mm
- High shock durability

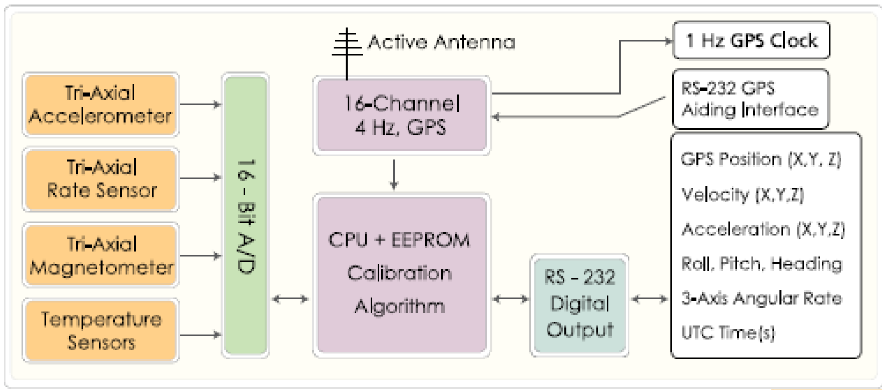
Adopted from: http://www.vti.fi/en/

Integrated IMUs

- Inertial Measurement Units
- Include typically:
  - 3 axis gyros
  - 3 axis accleration sensors
  - (Magnetometer)
  - (GPS)
  - (Odometry input)
  - Signal processor with internal data fusion
  - standard interface (RS-xxx, USB or CAN)
- Easy to use
- Measurement syncronization with external sensors can be a problem

Crossbow NAV420

- Real-Time GPS X, Y, Z Position and Velocity Outputs
- AHRS Pitch, Roll, and Heading Output at 100Hz
- Built-In GPS Receiver with RTCM and WAAS Compatibility
- High Stability MEMS Sensors
- 100 Hz Output Data Rate
- Enhanced Performance Kalman Filter Algorithm



Adopted from: http://www.xbow.com/Inertial_home.aspx

MicroStrain Inertia-Link

- Inertial Measurement Unit and Vertical Gyro utilizing miniature MEMS sensor technology
- triaxial accelerometer
- triaxial gyro
- temperature sensors
- on-board processor running a sophisticated sensor fusion algorithm
- http://www.microstrain.com/inertia-link.aspx

MicroStrain 3DM-GX1

- Three angular rate gyros
- three orthogonal DC accelerometers
- three orthogonal magnetometers
- multiplexer, 16 bit A/D converter and embedded microcontroller
- output its orientation in dynamic and static environments.
- update rates of 350 Hz
- [http://www.microstrain.com/3dm gx1.aspx](http://www.microstrain.com/3dm-gx1.aspx)