

Corso di Percezione Robotica (PRo)

Modulo C. Percezione Attiva

Percezione vestibolare

Cecilia Laschi
ARTS Lab, Scuola Superiore Sant'Anna
cecilia@arts.sssup.it
050-883486



Sommario della lezione

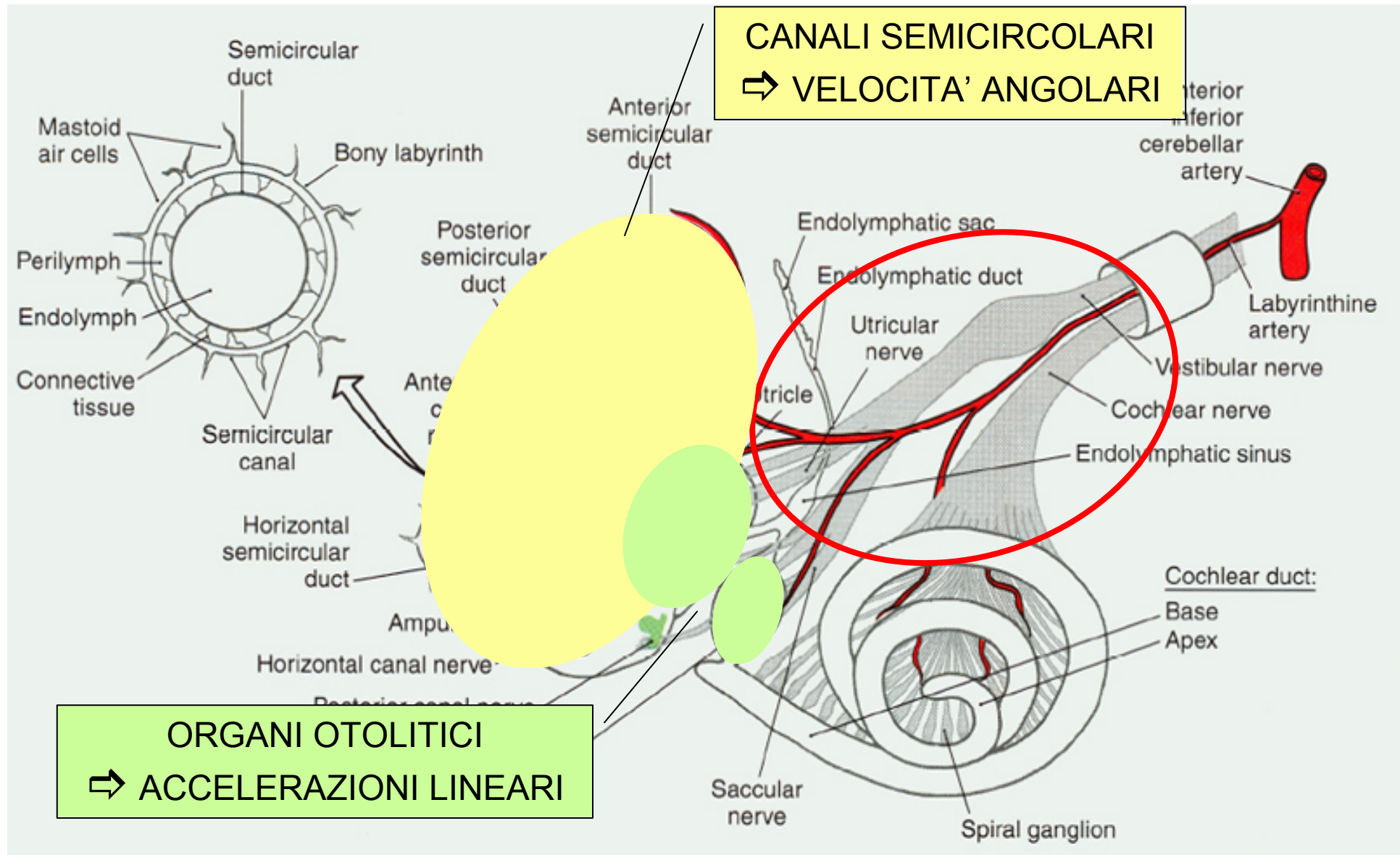
- Il sistema vestibolare nell'Uomo:
 - Funzioni e ruolo del sistema vestibolare nell'Uomo
 - Anatomia e neurofisiologia del sistema vestibolare
- Sistemi vestibolari artificiali
 - Dispositivi sensoriali funzionalmente analoghi:
 - accelerometri
 - giroscopi
- Possibili applicazioni dei sistemi vestibolari artificiali in biorobotica



Sistema vestibolare

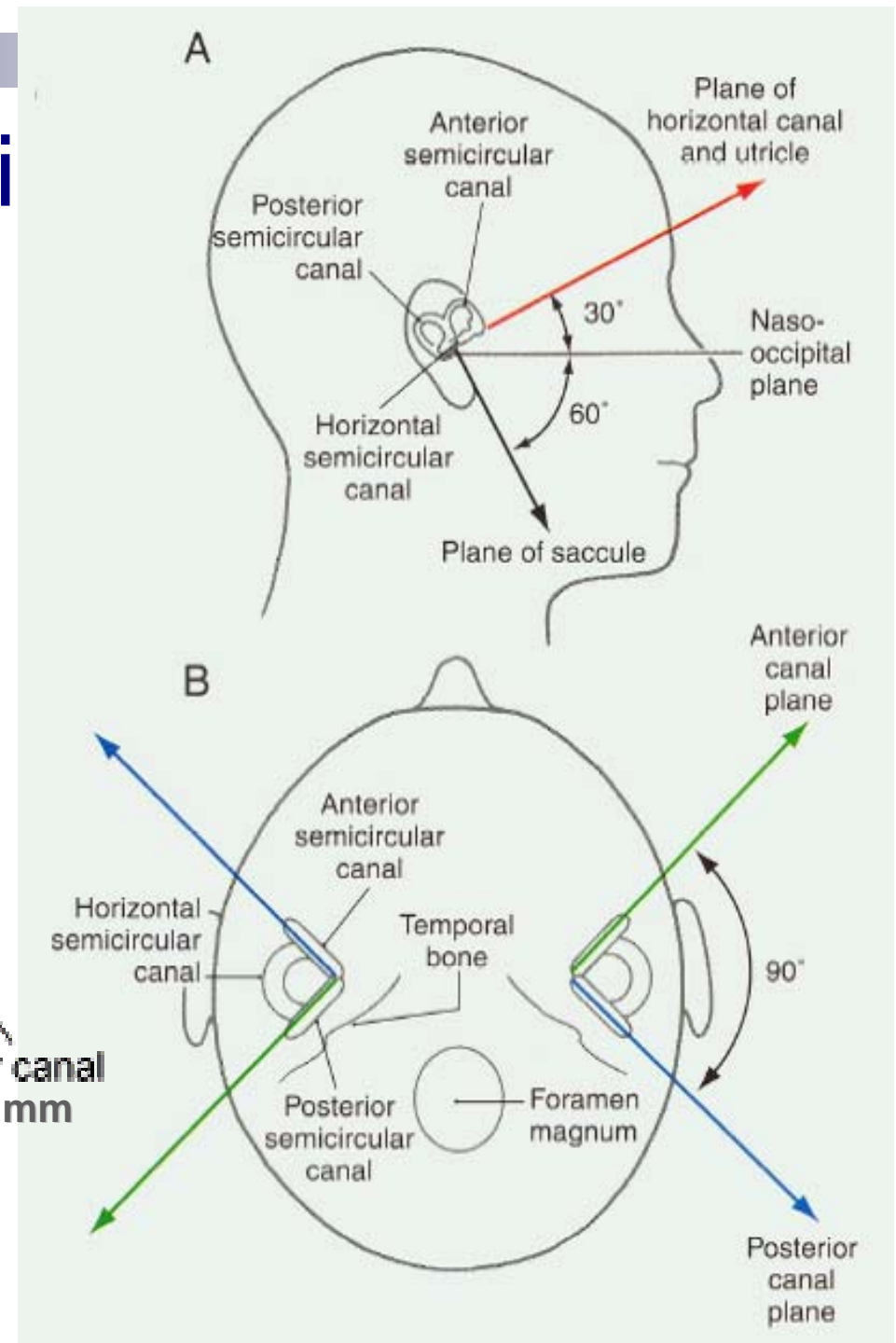
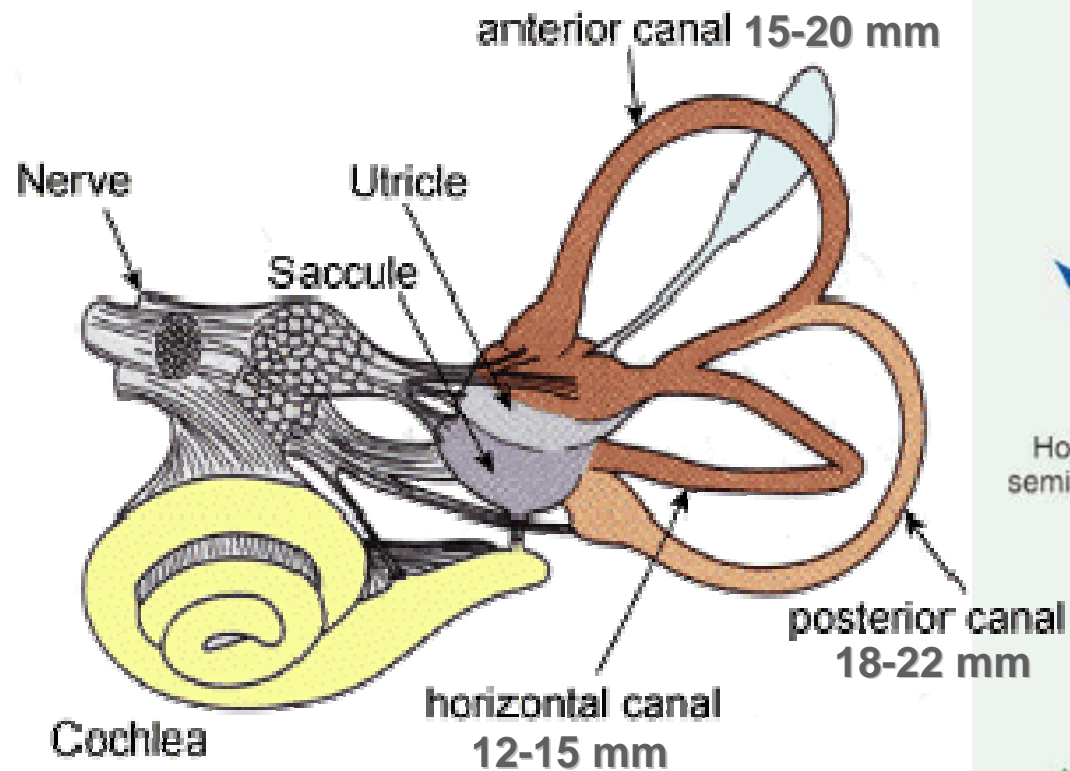
- “Organo dell’equilibrio”
- Sensibile a:
 - ☐ movimenti della testa
 - ☐ posizione della testa nello spazio
- Misura:
 - ☐ velocità angolari
 - ☐ accelerazioni lineari
- Ruolo fondamentale, a livello inconscio, in varie funzioni motorie:
 - ☐ controllo della postura
 - ☐ coordinazione dei movimenti
 - ☐ controllo dei movimenti oculari

Il sistema vestibolare umano



I canali semicircolari

2/3 di circonferenza di diametro 6,5 mm
diametro interno: 0,4 mm

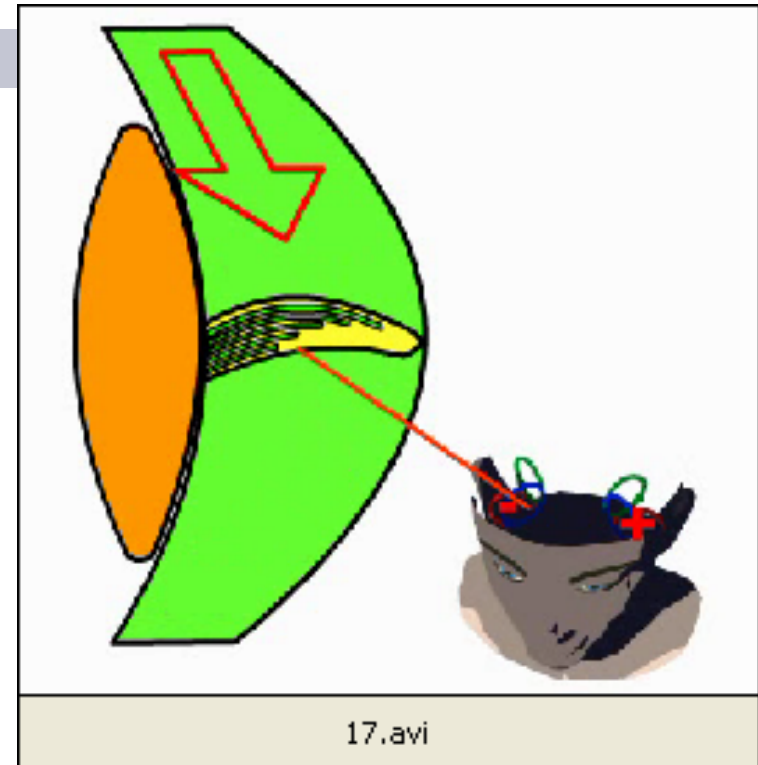


I canali semicircolari

- Oscillatore smorzato

$$\theta(s) = \frac{\alpha s}{(T_1 s + 1)(T_2 s + 1)} \dot{q}(s)$$

Si comporta come un integratore

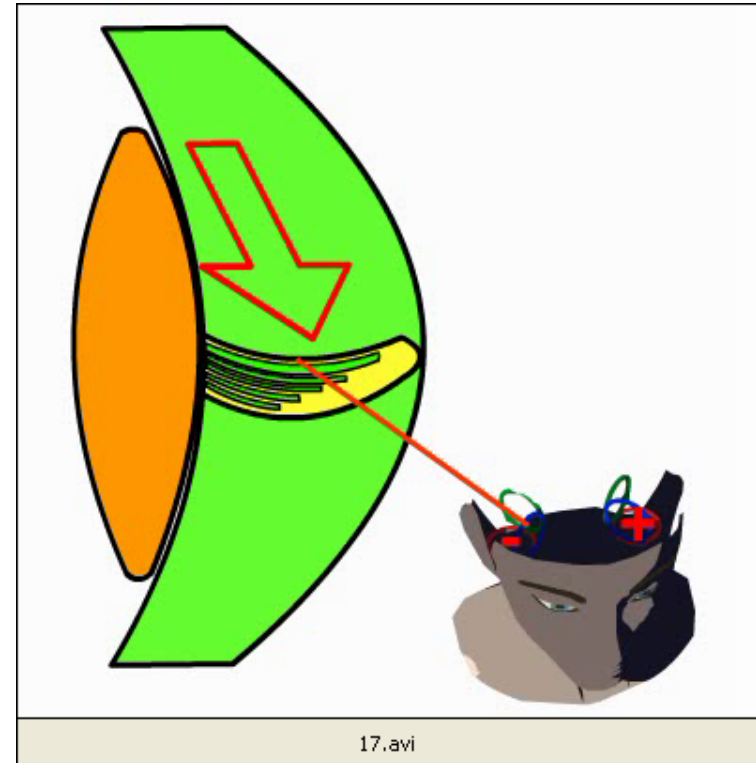


- con θ = deflessione della cupula, \dot{q} = velocità della testa, α = fattore proporzionale e s = frequenza
- Nell'Uomo, le costanti di tempo T_1 e T_2 sono approssimativamente 3 ms and 5 s, rispettivamente
- Per movimenti tipici della testa, con frequenze da 0.1 Hz a 10 Hz, la deflessione della cupula è approssimativamente proporzionale alla velocità della testa

I canali semicircolari

■ Assumendo l'endolinfa con

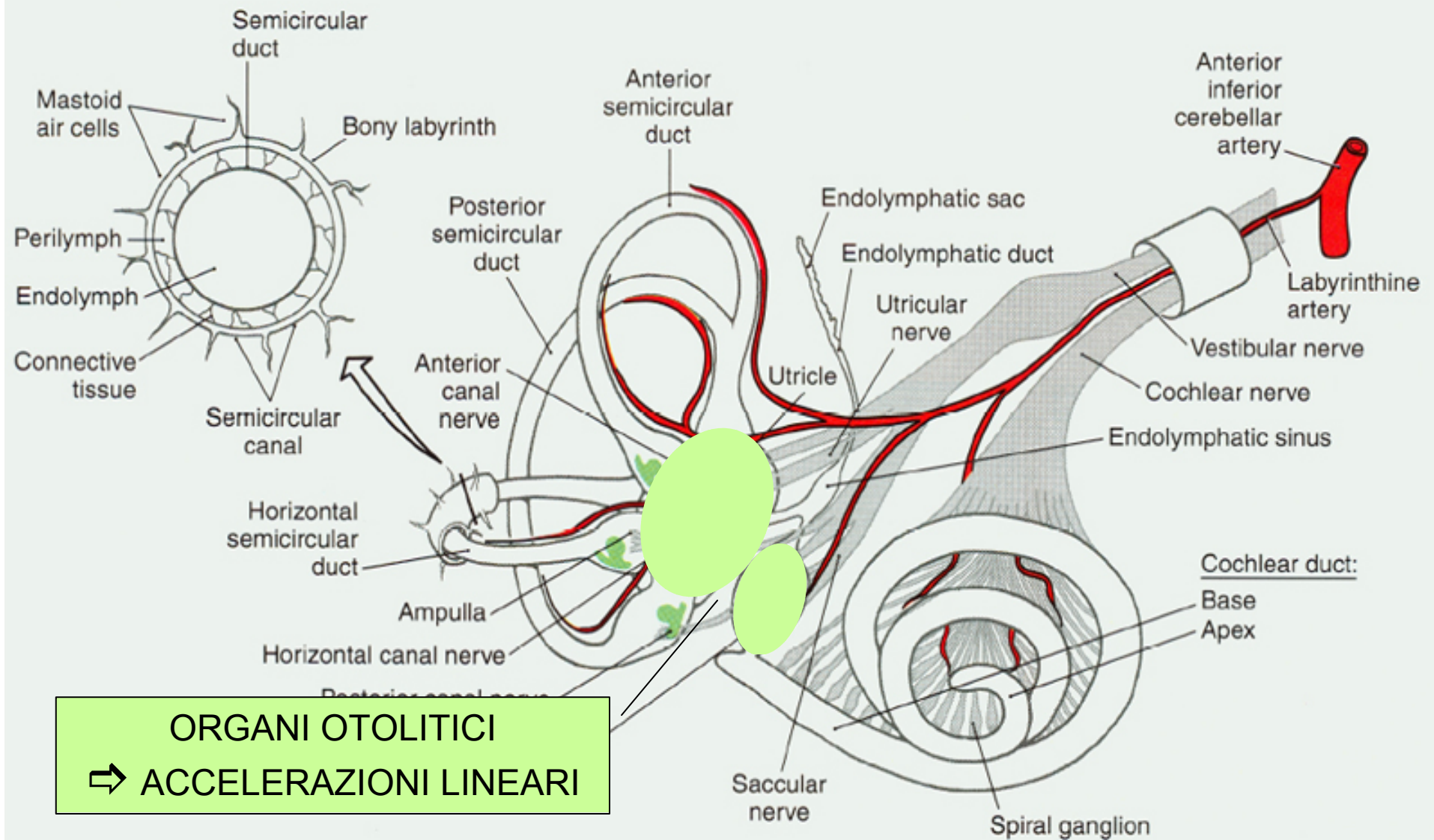
- densità $\rho = 1,0 \text{ g/cm}^3$
- viscosità $\mu = 0,01 \text{ g/cm/s}$



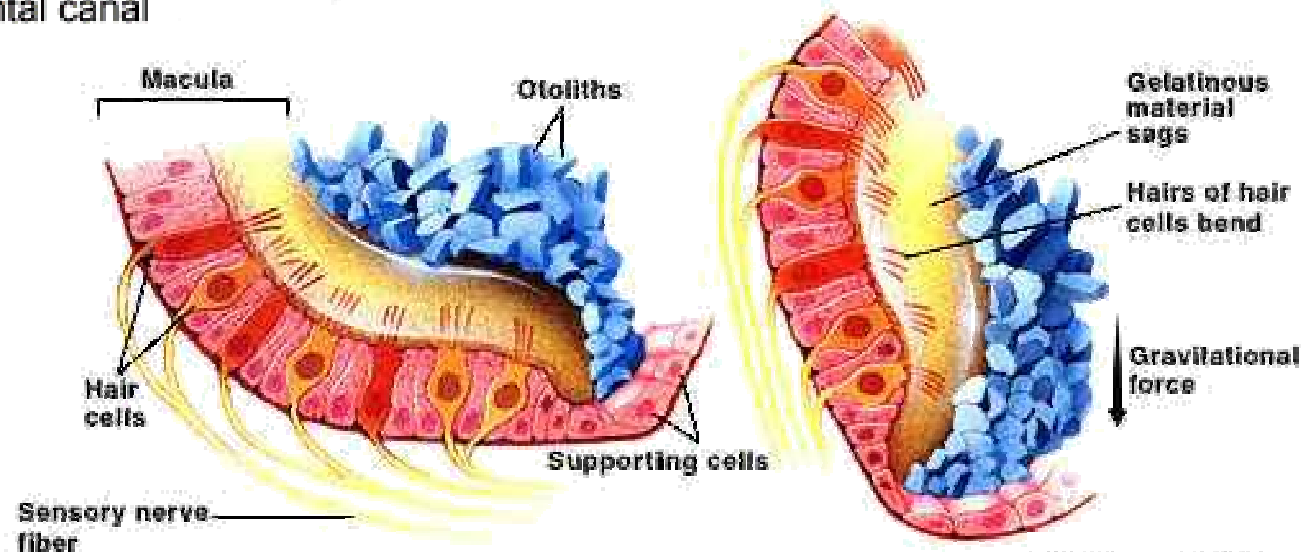
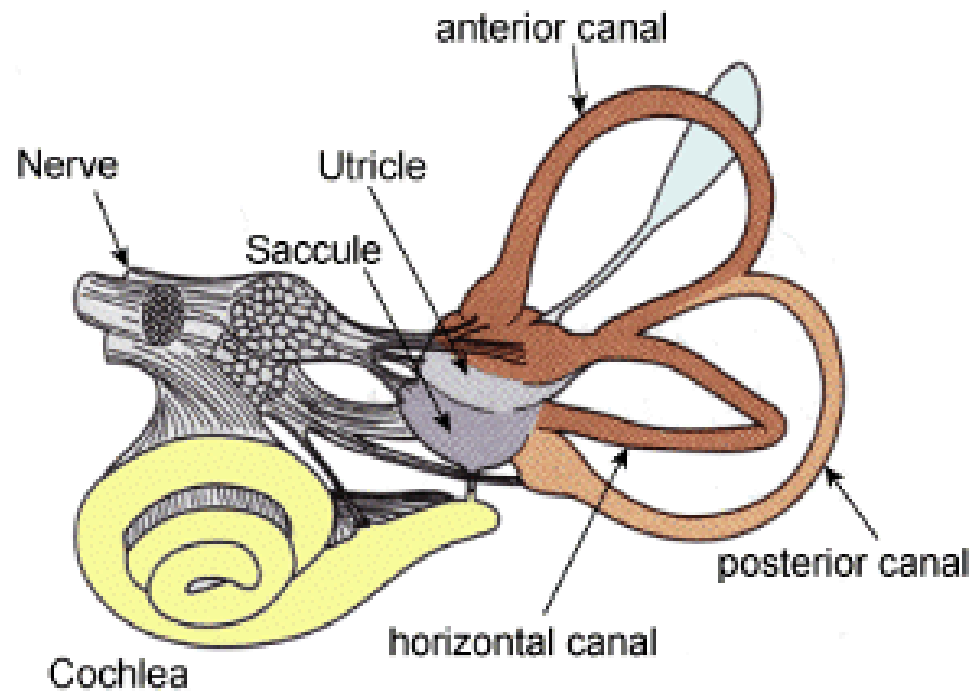
	Sforzo X	Sforzo Y	Sforzo Z	Sforzo XY	Sforzo YZ	Sforzo XZ
Max Values [Pa]	-0.89	-0.899	1.000	0.306	0.552	0.552
Min Values [Pa]	0.8	0.8	0	0.3	0.50	0.50

	deformazione X	deformazione Y	deformazione Z	deformazione XY	deformazione YZ	deformazione XZ
Max values	0.62 (e-4)	0.62 (e-4)	0.30 (e-4)	0.63(e-4)	0.11 (e-3)	0.11 (e-3)
Min values	-0,61 (e-4)	-0.62 (e-4)	-0.82 (e-4)	-0.63 (e-4)	-0.11 (e-3)	-0.11(e-3)

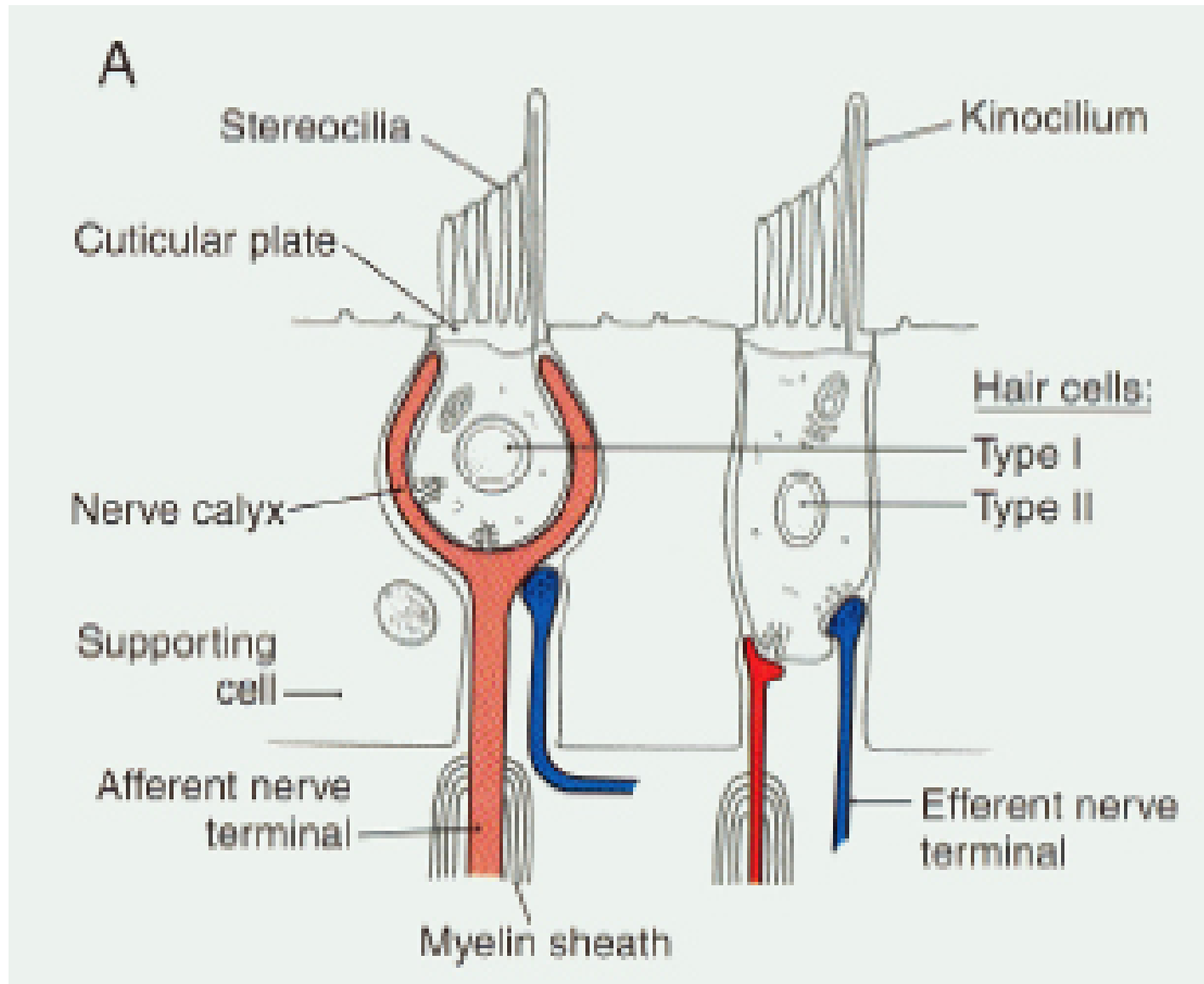
Gli organi otolitici



Gli organi otolitici



I recettori vestibolari



I recettori vestibolari

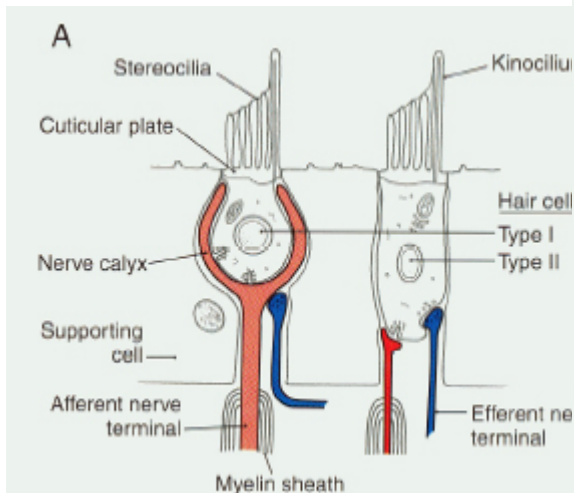
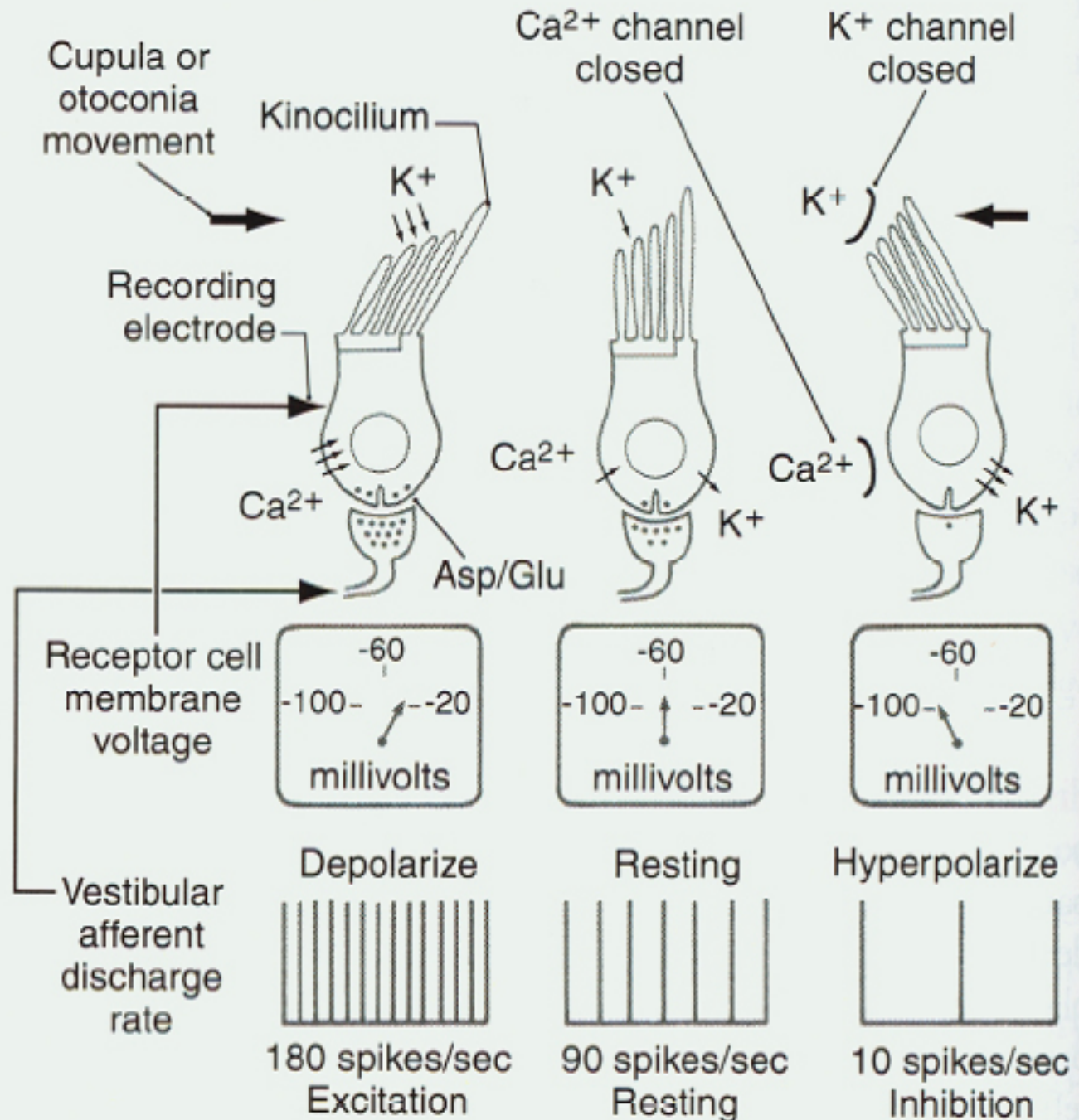
How is motion transduced into neural firing?

The steps are.

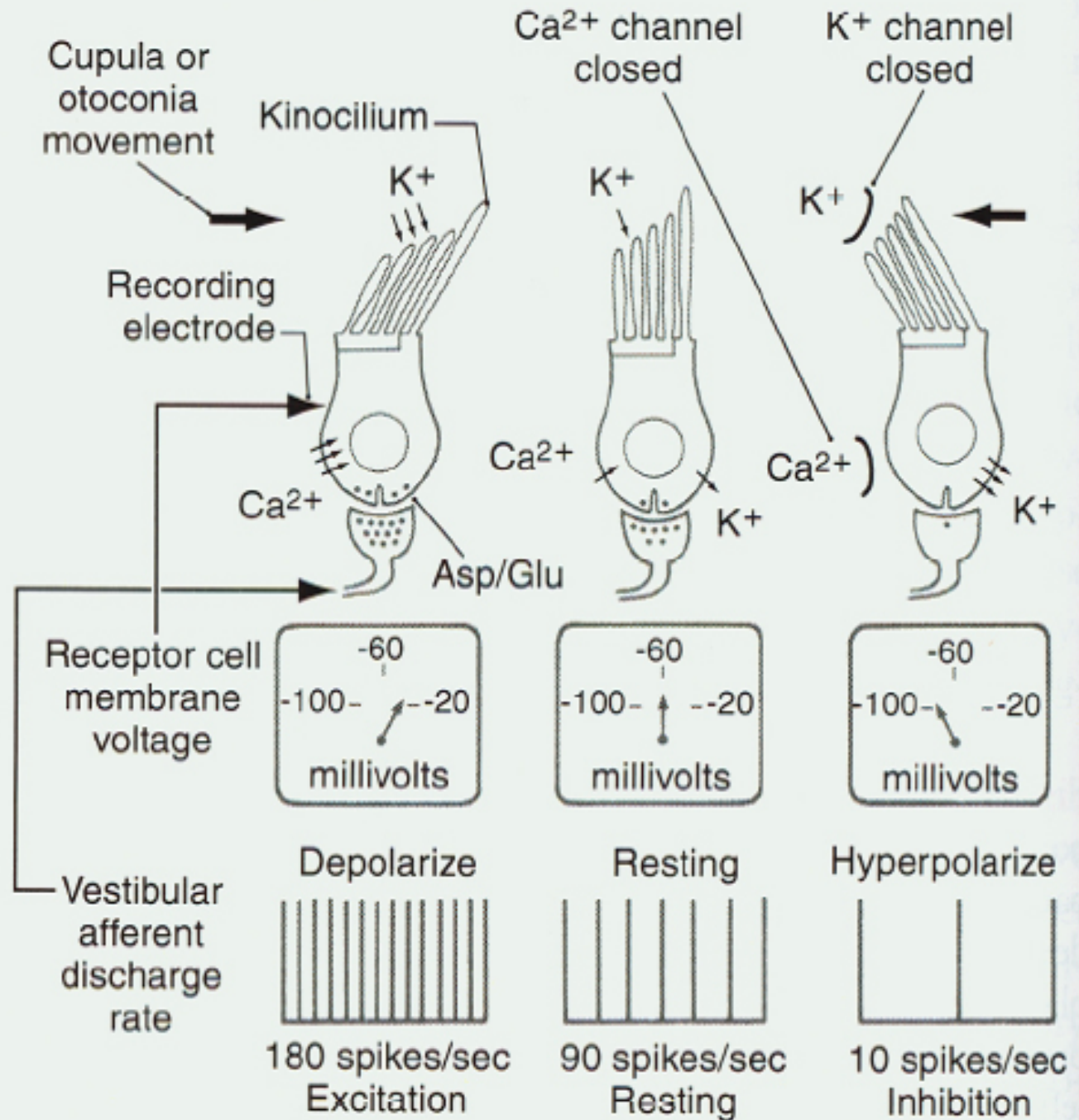
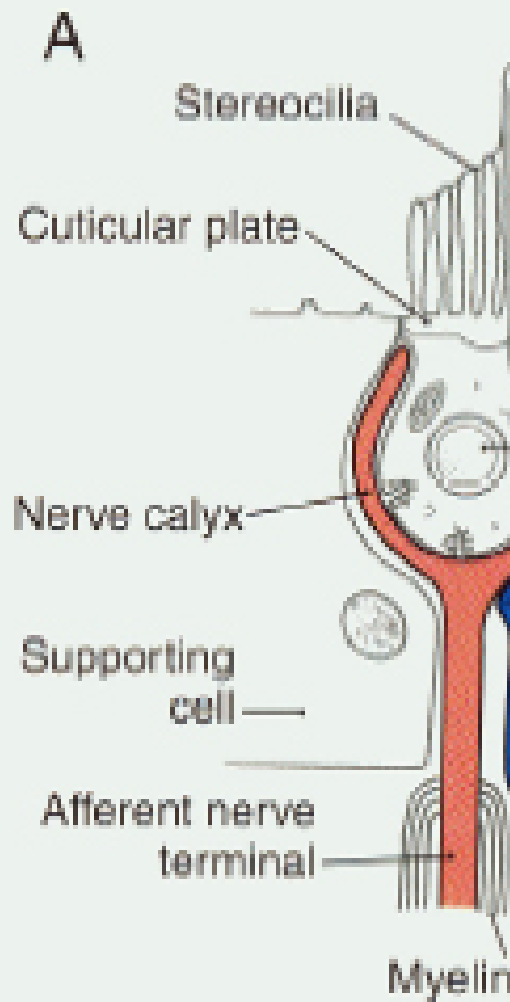
- 1) As in auditory hair cells, motion bends the hairs.
- 2) The filament between adjacent hairs opens ion channels allowing K^+ to enter the hair cell.
- 3) The hair cell depolarizes, releasing neurotransmitter.
- 4) There is an increase in the frequency of AP's in the bipolar 8th nerve afferent.



I recettori vestibolari

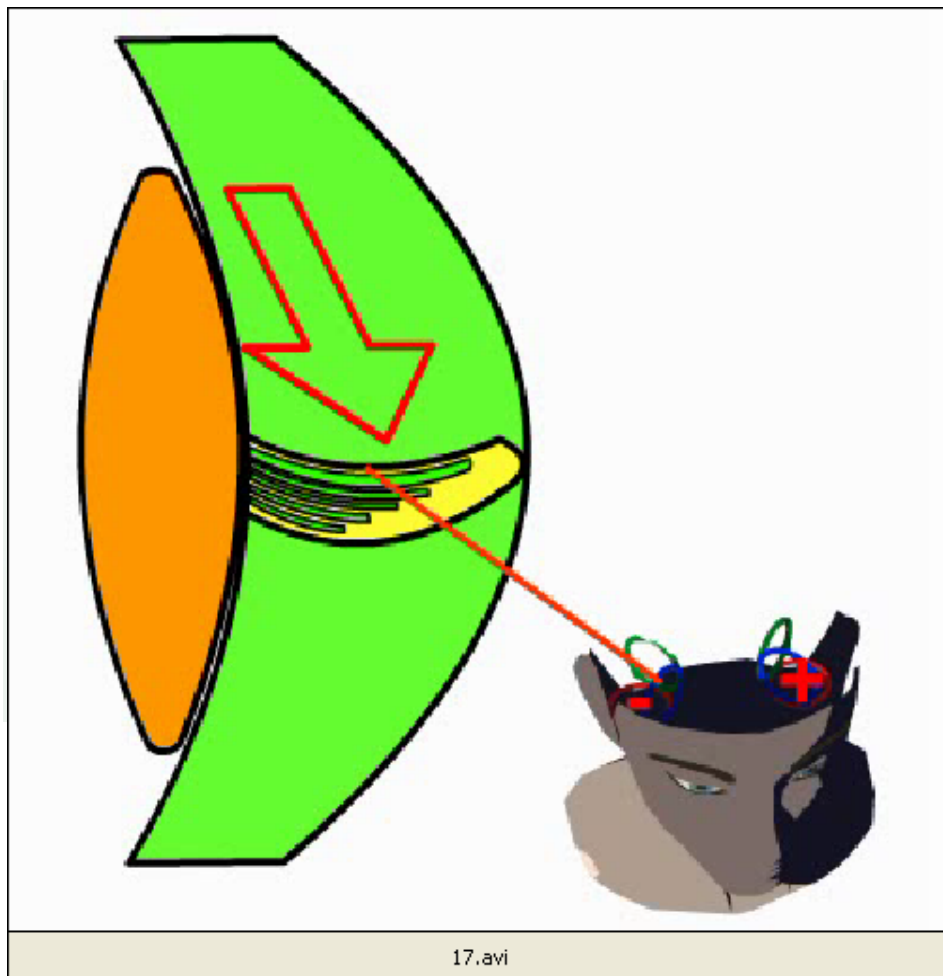


I recettori vestibolari

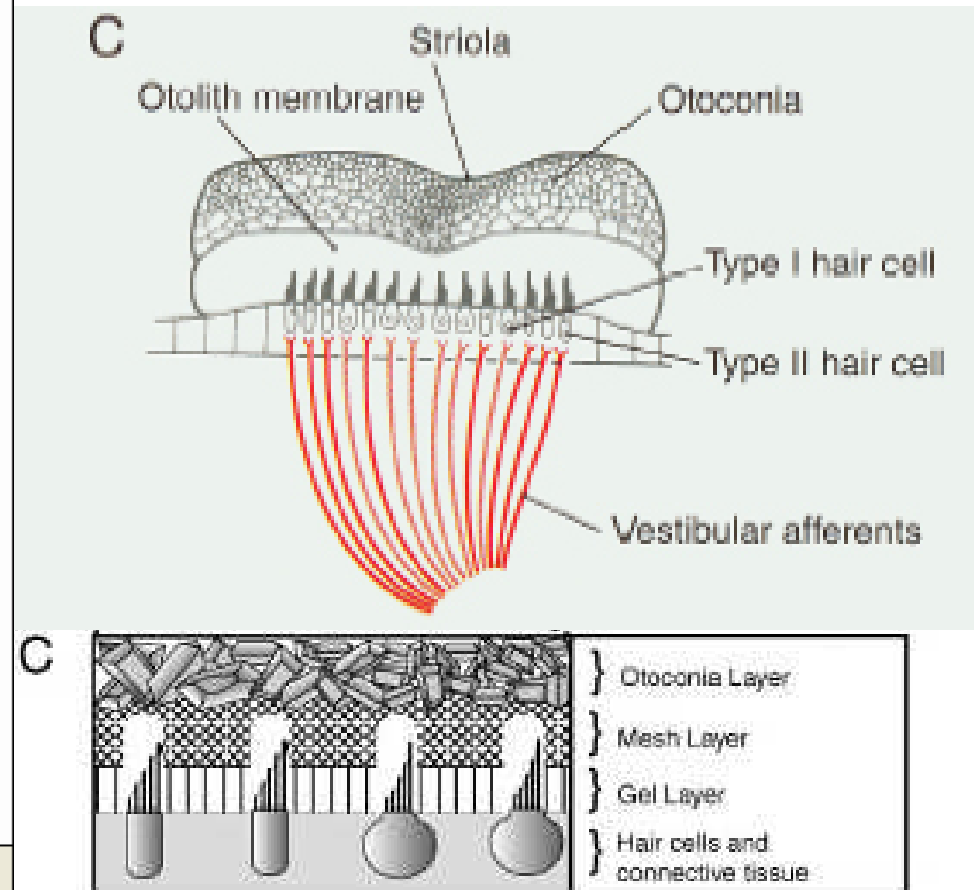


I recettori vestibolari nei canali semicircolari e negli organi otolitici

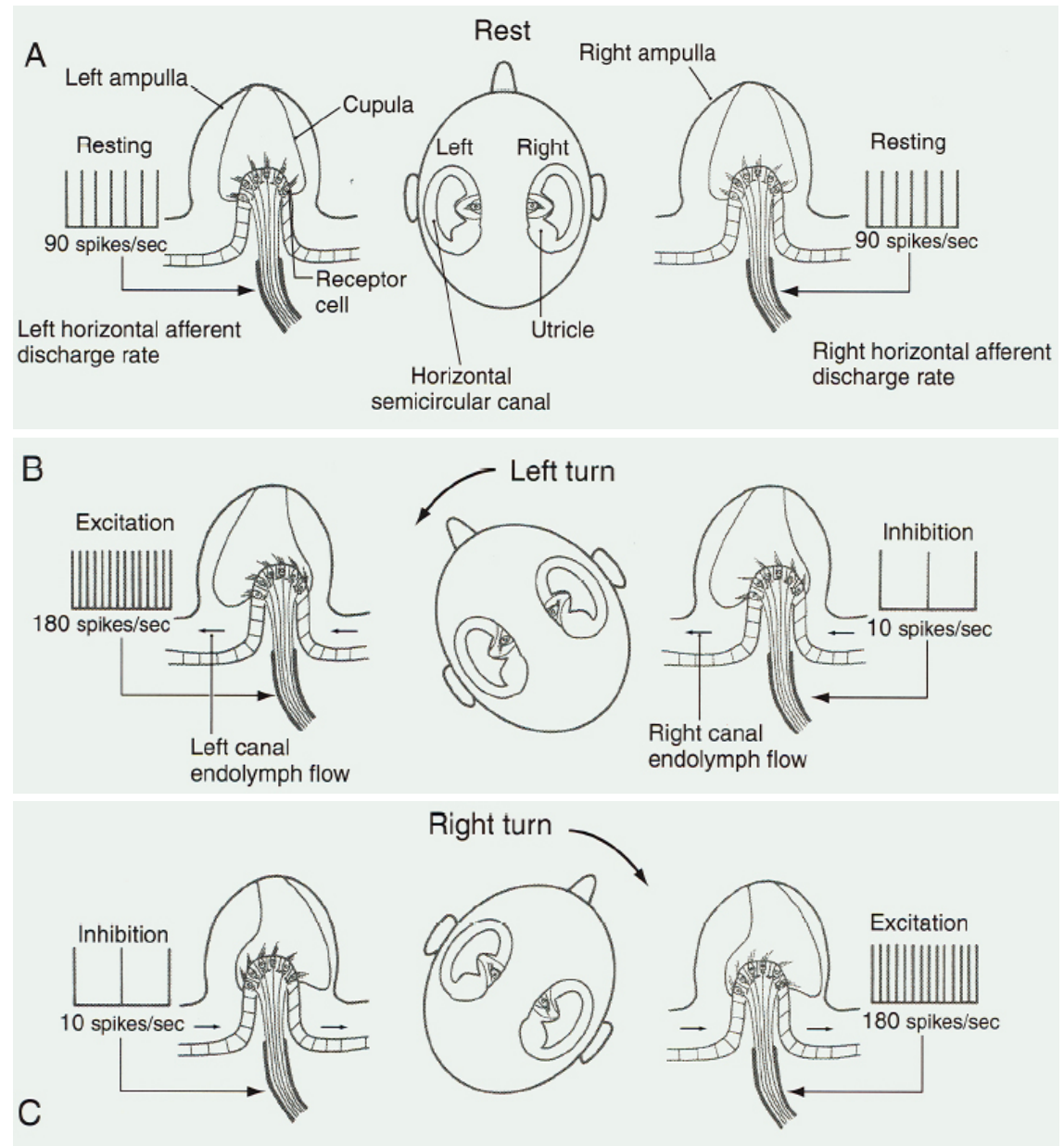
■ Canali semicircolari



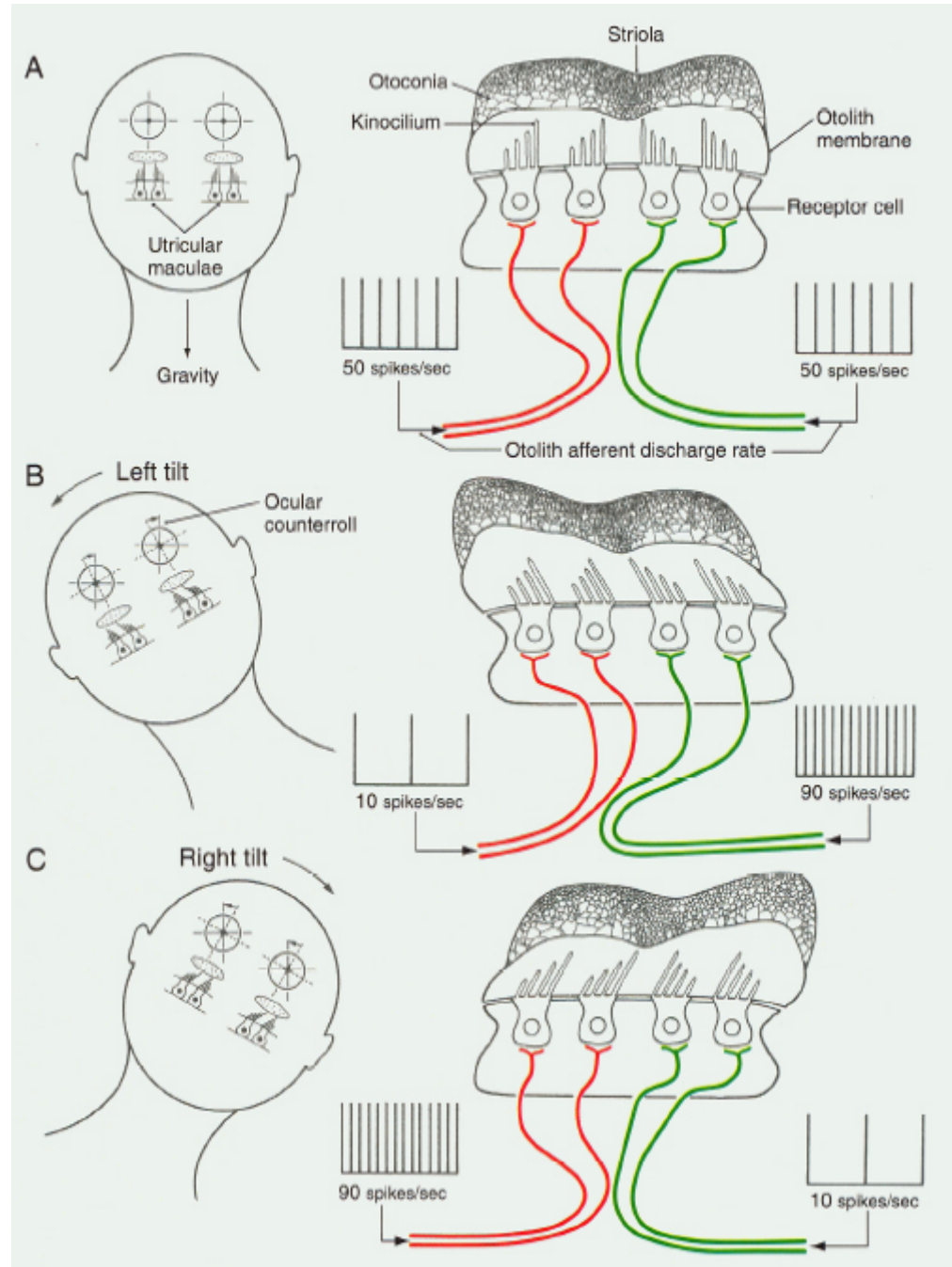
■ Organi otolitici



Meccanismo di risposta dei canali semicircolari alle rotazioni della testa



Meccanismo di risposta degli organi otolitici alle inclinazioni della testa



Human Vestibular System

Canals work in pairs.


The canals are arranged such that each canal has a partner on the other side of the head.

When one partner is maximally excited, the other is maximally inhibited.

This is called push-pull organization.

When the head rotates rightward, excitation occurs in the right horizontal canal on the right side of the head and inhibition occurs in the left.

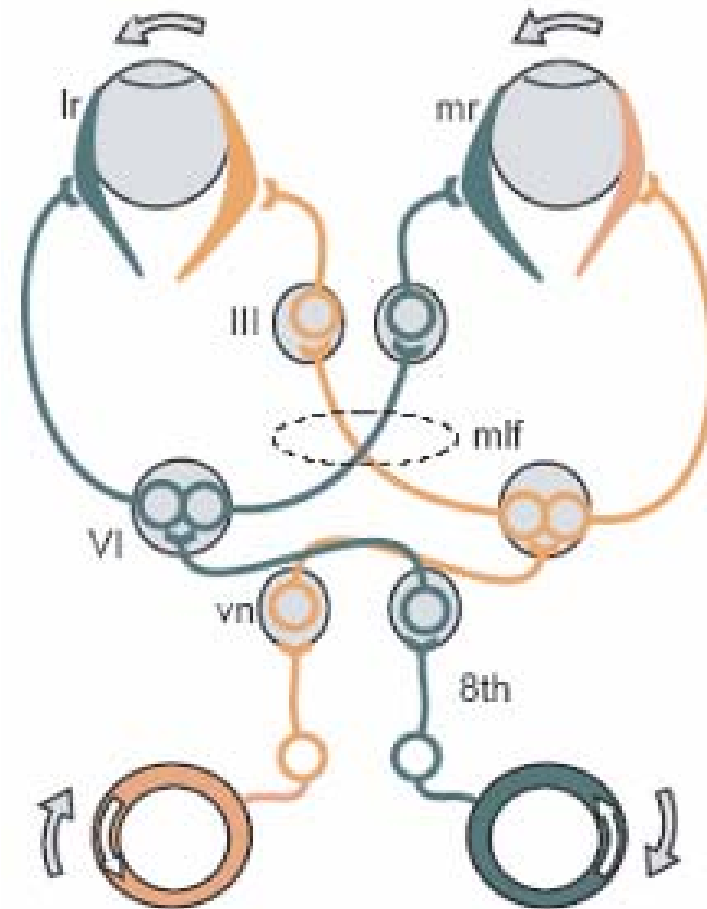
The anterior canal on one side and the posterior on the other also form push-pull pairs.



Start Labyrinth Otoliths Canals VOR Dizzy Plasticity End

undici.avi

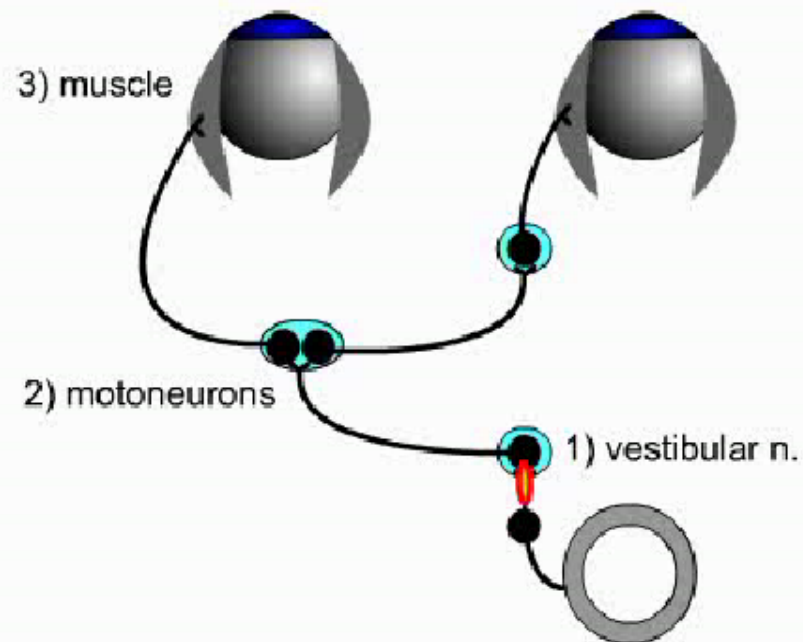
Il Riflesso Vestibulo-Oculare (VOR)



II Riflesso Vestibulo-Oculare (VOR)

Explain the neural mechanism for a horizontal VOR.

The direct path is a short reflex with 3 synapses.



Start Labyrinth Otoliths Canals VOR Dizzy Plasticity End



Explain the neural mechanism for a horizontal VOR.

When the head rotates rightward the following occurs.

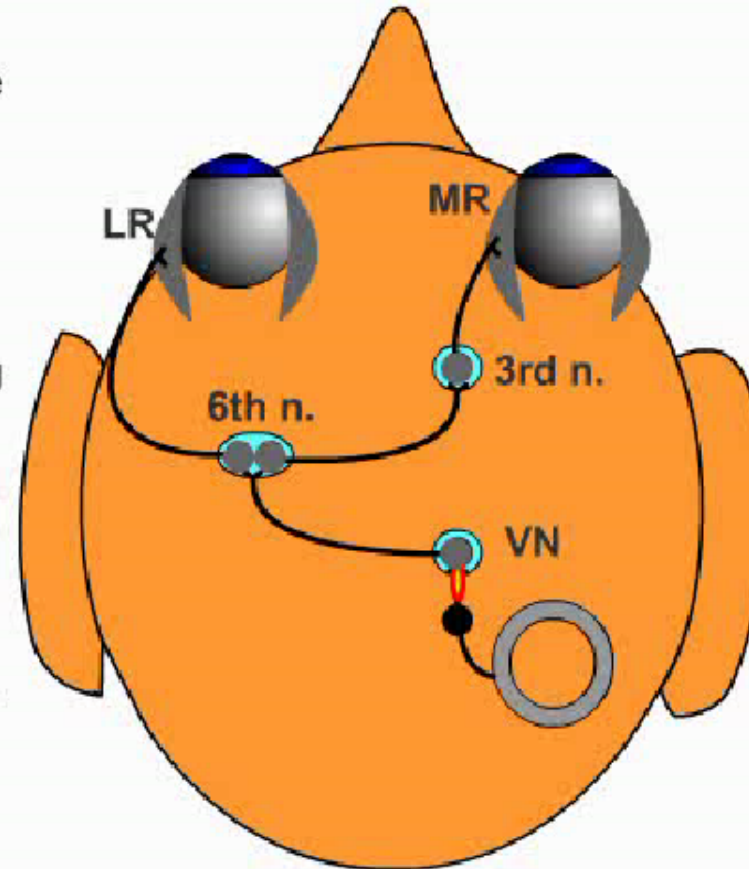
The right horizontal canal hair cells depolarize.

The right vestibular nucleus (VN) firing rate increases.

The motoneurons (in the right 3rd and left 6th nuclei) fire at a higher frequency.

The left lateral rectus (LR) extraocular muscle and the right medial rectus (MR) contract.

Both eyes rotate leftward.



Start Labyrinth Otoliths Canals VOR Dizzy Plasticity End



II Riflesso Vestibulo-Oculare (VOR)

Explain the neural mechanism for a horizontal VOR.

The VOR is a push-pull reflex.
Neurons on other side do the opposite.

When the **head rotates rightward** the following occurs.

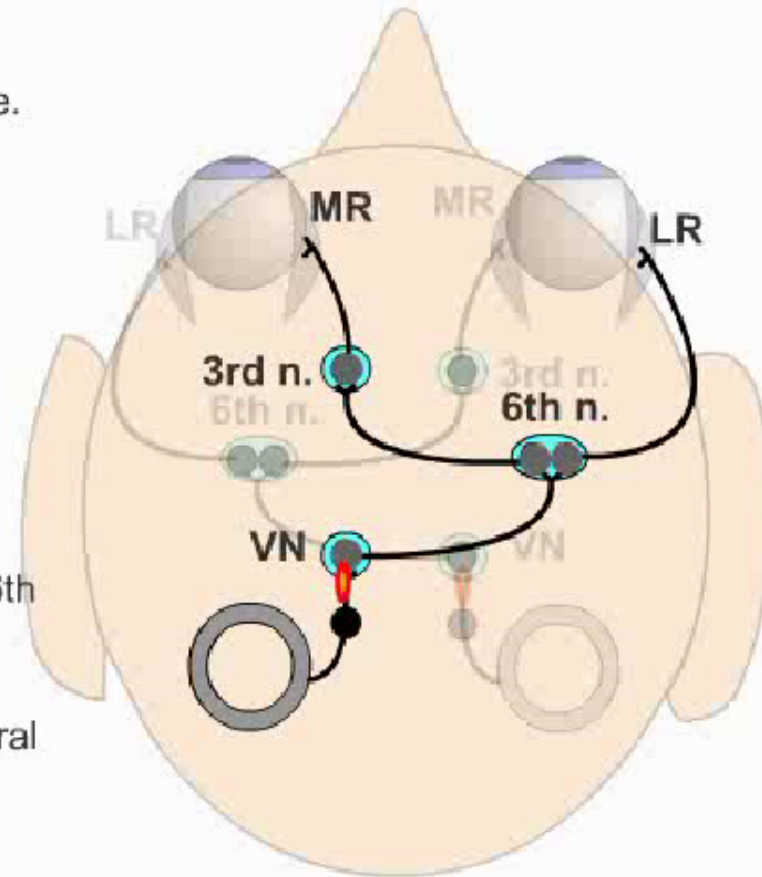
The left horizontal canal hair cells hyperpolarize.

The left vestibular nucleus firing rate decreases.

Motor neurons in the left 3rd and right 6th nuclei fire at a lower frequency.

The left medial rectus and the right lateral rectus relax.

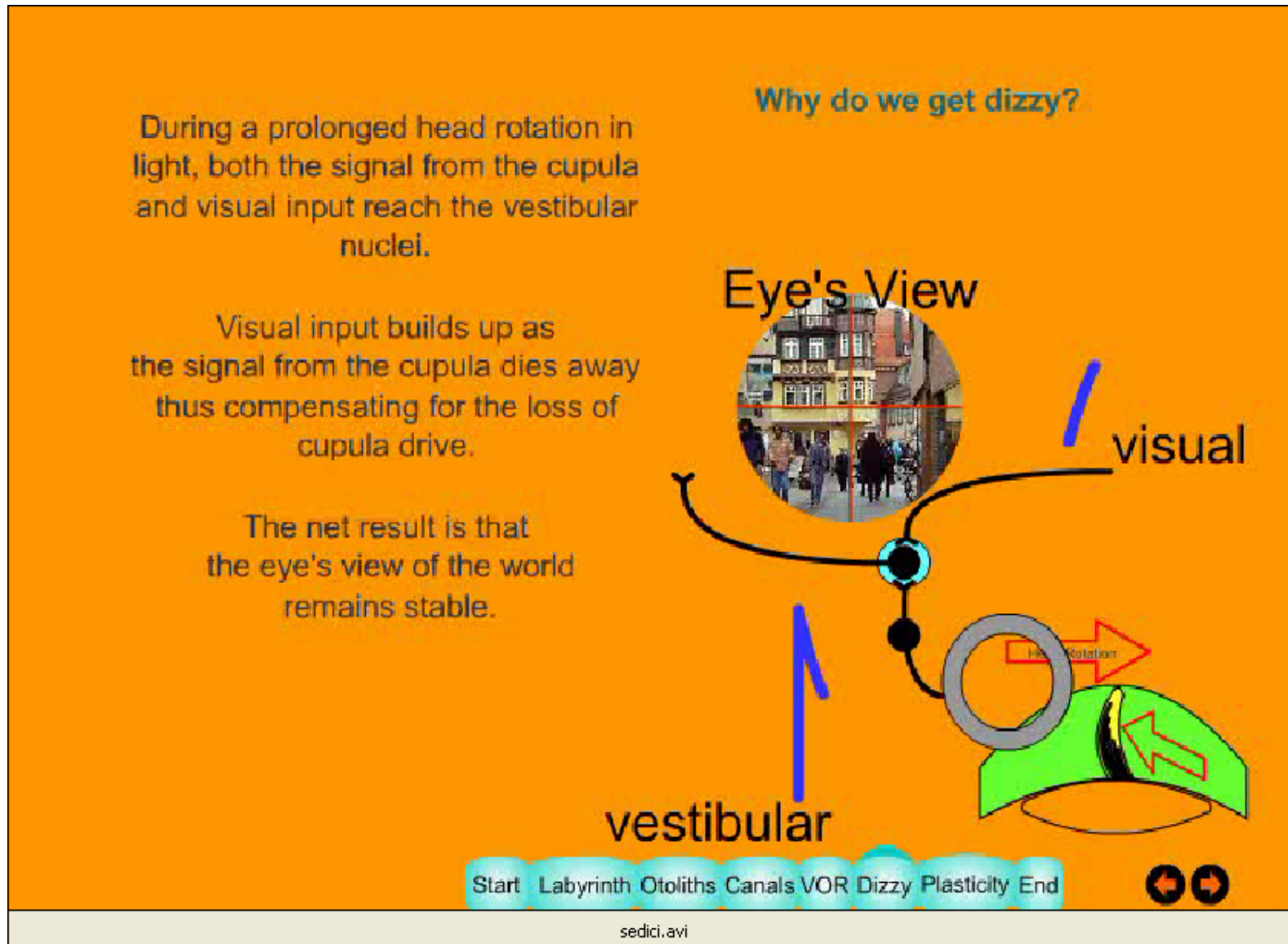
This helps the **eyes rotate leftward**.



Start Labyrinth Otoliths Canals VOR Dizzy Plasticity End



II Riflesso Vestibulo-Oculare (VOR)





Sommario della lezione

- Il sistema vestibolare nell'Uomo:
 - Funzioni e ruolo del sistema vestibolare nell'Uomo
 - Anatomia e neurofisiologia del sistema vestibolare
- **Sistemi vestibolari artificiali**
 - **Dispositivi sensoriali funzionalmente analoghi:**
 - **accelerometri**
 - **giroscopi**
- Possibili applicazioni dei sistemi vestibolari artificiali in biorobotica

Quantità cinematiche

■ Posizione

□ $x(t); \theta(t)$

■ Velocità

□ $v(t); \omega(t)$

■ Accelerazione

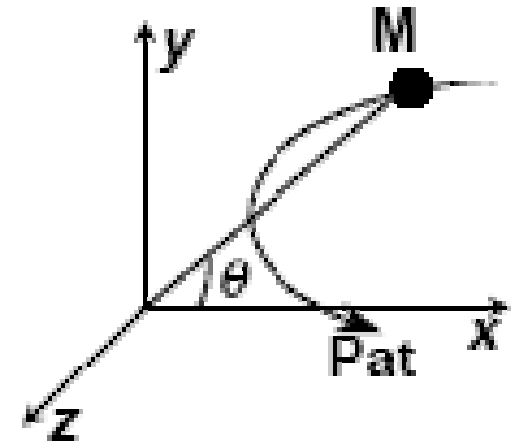
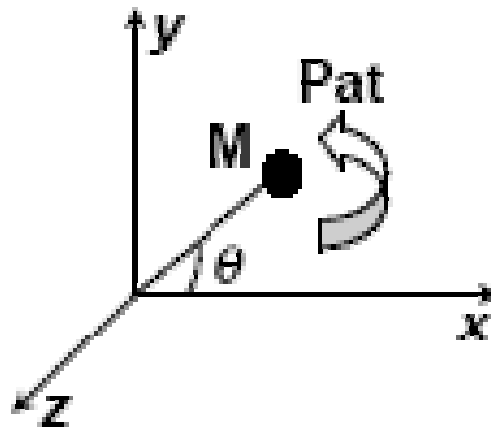
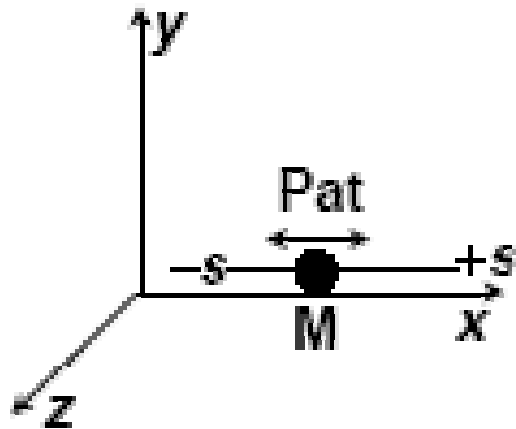
□ $a(t); \alpha(t)$

■ Jerk

□ ...

The diagram illustrates the relationship between kinematic quantities through differentiation and integration. It consists of three rows, each corresponding to a level of motion. On the left side, there are three curved arrows pointing downwards, each containing the derivative operator $\frac{d}{dt}$. On the right side, there are three curved arrows pointing upwards, each containing the integral operator $\int dt$. The rows are aligned such that the derivative arrows point from the quantity above to the quantity below, and the integral arrows point from the quantity below to the quantity above. This indicates that differentiation reduces the order of the quantity, while integration increases it.

Tipi di moto



■ Rettilineo:

$$a = \frac{dv}{dt} = \frac{d(ds/dt)}{dt} = \frac{d^2s}{dt^2}$$

■ Angolare:

$$\alpha = \frac{d\omega}{dt} = \frac{d(d\theta/dt)}{dt} = \frac{d^2\theta}{dt^2}$$

■ Curvilineo:

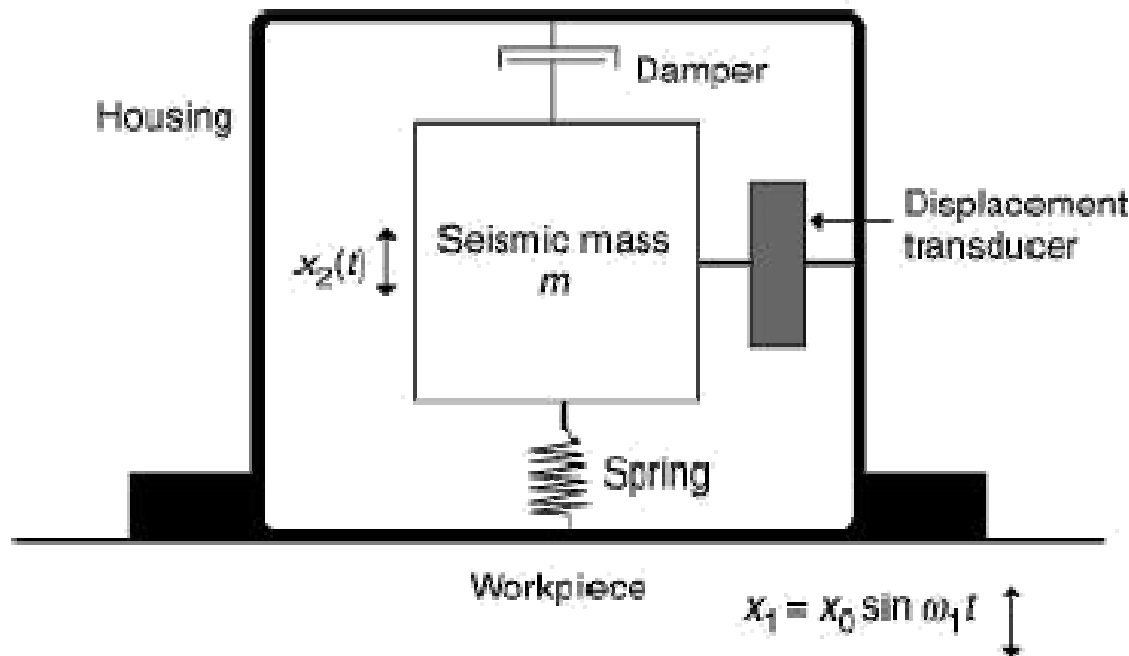
$$\mathbf{a} = \frac{d\mathbf{v}}{dt} = \frac{d^2x}{dt^2}\mathbf{i} + \frac{d^2y}{dt^2}\mathbf{j} + \frac{d^2z}{dt^2}\mathbf{k}$$



Misura dell'accelerazione

- DIRETTA: attraverso accelerometri
- INDIRETTA: derivando la velocità
- Nei moti rettilinei o angolari è preferibile la misurazione diretta
- Nei moti curvilinei l'accelerazione è misurata con metodi indiretti

Principio di funzionamento tipico degli accelerometri



$$f(t) = m \frac{d^2 x}{dt^2} + c \frac{dx}{dt} + kx$$

$$m \frac{d^2 z}{dt^2} + c \frac{dz}{dt} + kz = mg \cos(\theta) - m \frac{d^2 x_1}{dt^2}$$

$$z = x_2 - x_1$$

$\theta = \text{angolo rispetto alla gravità}$

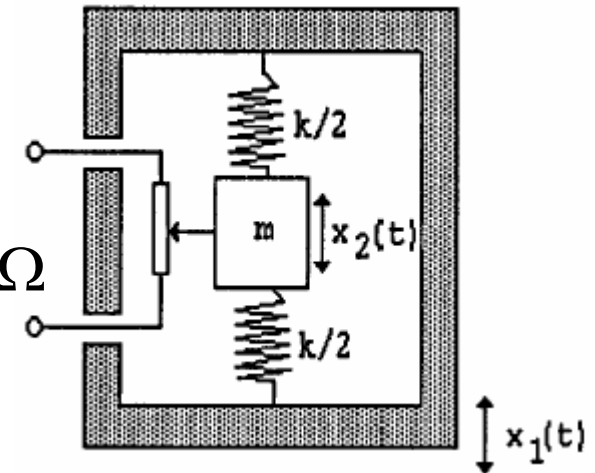


Principali tecnologie

- Inerziali e meccaniche
- Piezoelettriche
- Piezoresistive
- Strain gauges
- Induttive
- Micro- e nano-fabbricazione

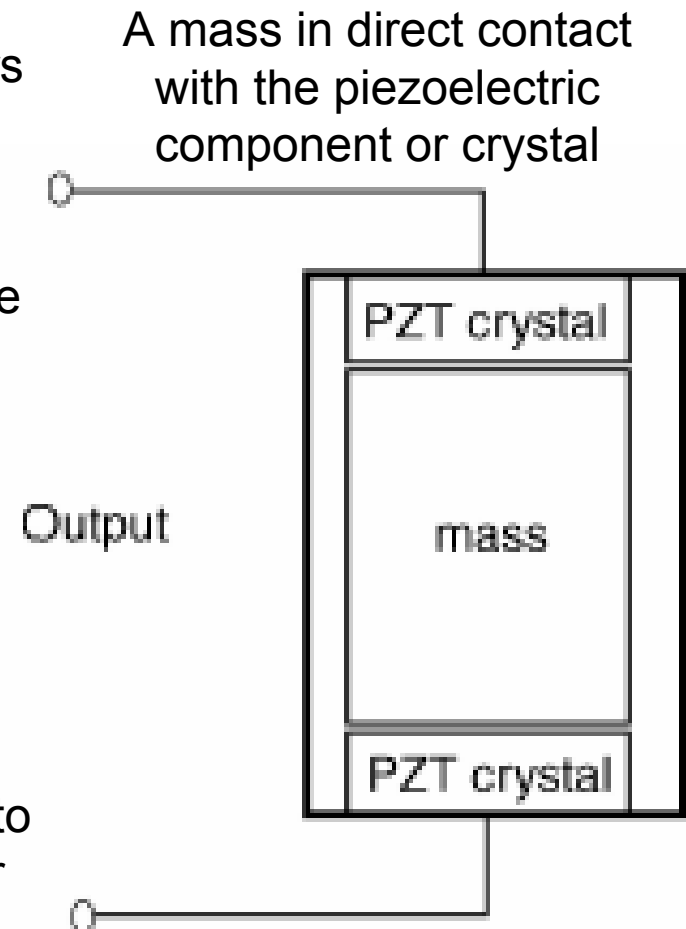
Accelerometri potenziometrici

- Un potenziometro è usato per misurare lo spostamento relativo tra la massa sismica e la base
 - Un liquido viscoso interagisce continuamente con la base e la massa per fornire lo smorzamento
- Bassa frequenza di operazione (inferiore a 100 Hz)
 - Soprattutto per le accelerazioni con variazioni lente e vibrazioni a bassa frequenza
- Range dinamico tipico: $\pm 1g$ to $\pm 50g$ fs.
- Frequenze naturali: 12- 89 Hz,
- Rapporto di smorzamento ζ : 0.5- 0.8
- Resistenza del potenziometro: 1000–10000 Ω
 - Risoluzione corrispondente: 0.45–0.25% fs.
- Sensibilità cross- assiale: $< \pm 1\%$.
- Accuratezza: $\pm 1\%$ fs a temperatura ambiente.
- Dimensioni: 50mm³ (<0.1 gr.)



Accelerometri piezoelettrici

- Piezoelectric accelerometers are widely used for general-purpose acceleration, shock, and vibration measurements. They are basically motion transducers with large output signals and comparatively small sizes.
- When a varying motion is applied to the accelerometer, the crystal experiences a varying force excitation ($F = ma$), causing a proportional electric charge q to be developed across it.
- These accelerometers are useful for high-frequency applications.
- Piezoelectric accelerometers are available in a wide range of specifications. They are manufactured as small as 3 x 3 mm in dimension with about 0.5 g in mass, including cables. They have excellent temperature ranges and some of them are designed to survive the intensive radiation environment of nuclear reactors. However, piezoelectric accelerometers tend to have larger cross-axis sensitivity than other types, about 2–4%.

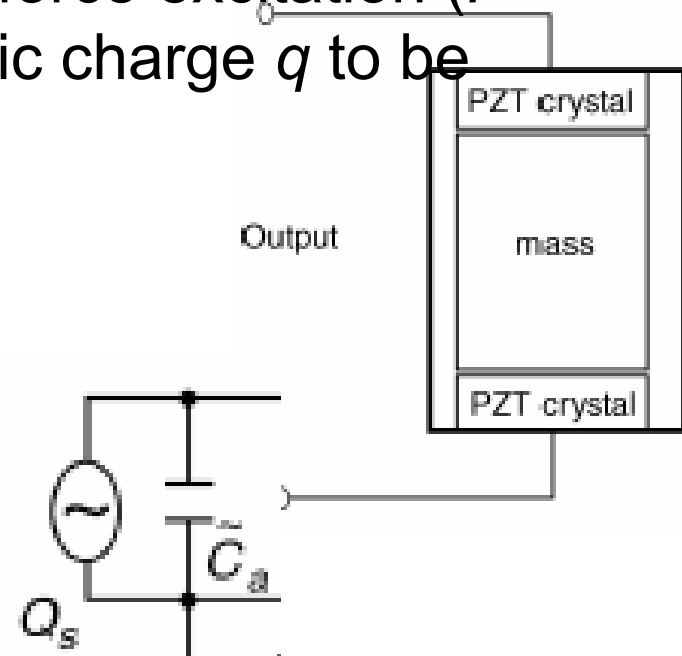


Piezoelectric accelerometers

- A mass in direct contact with the piezoelectric component or crystal
- When a varying motion is applied to the accelerometer, the crystal experiences a varying force excitation ($F = ma$), causing a proportional electric charge q to be developed across it.

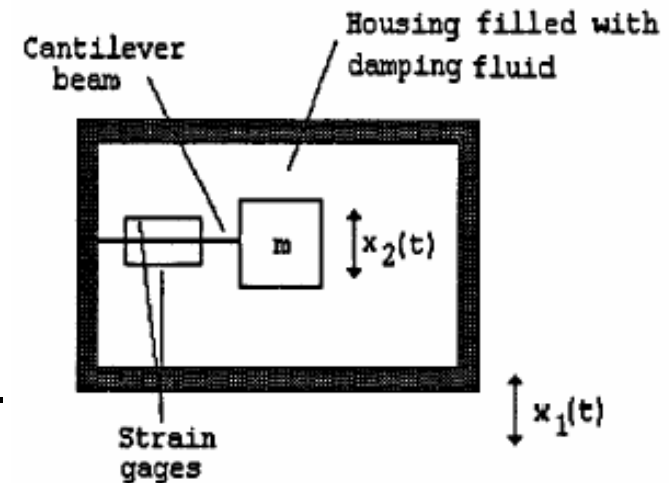
$$Q_s|_{V=const} = d_{ij} F = d_{ij} ma$$

- d_{ij} is the piezoelectric constant
- Q_s is the developed charge
- The output impedance is capacitive



Accelerometri a strain gauge

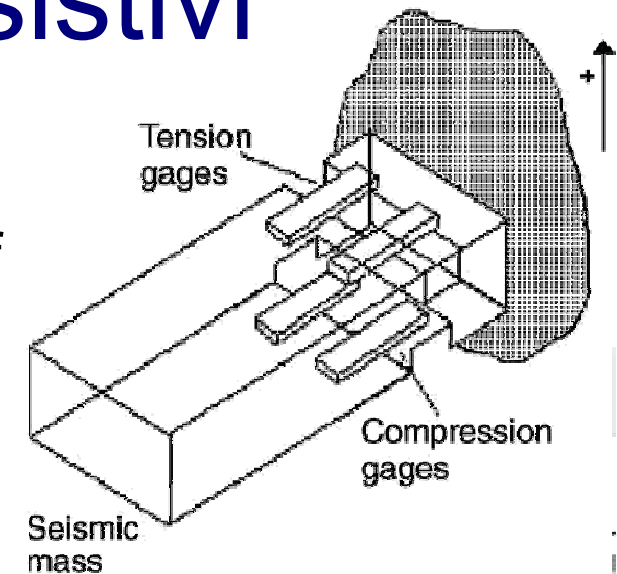
- Electric resistance strain gauges are also used for displacement sensing of the seismic mass
 - the seismic mass is mounted on a cantilever beam rather than on springs.



- Resistance strain gages are bonded on each side of the beam to sense the strain in the beam resulting from the vibrational displacement of the mass.
- Damping for the system is provided by a viscous liquid filling the housing.
- The output of the strain gages is connected to an appropriate bridge circuit.
- The natural frequency of such a system is about 300 Hz.
 - The low natural frequency is due to the need for a sufficiently large cantilever beam to accommodate the mounting of the strain gages.

Accelerometri piezoresistivi

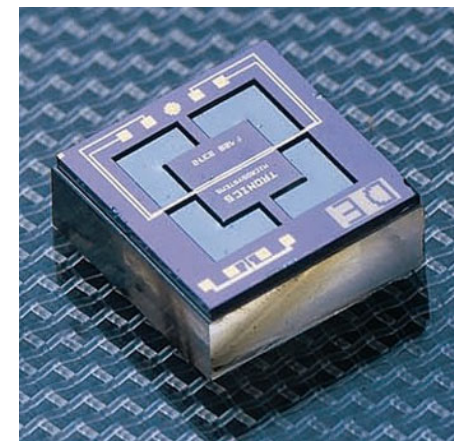
- Piezoresistive accelerometers are essentially semiconductor strain gauges with large gauge factors. The sensitivity of a piezoresistive sensor comes from the elastic response of its structure and resistivity of the material.
- Piezoresistive accelerometers are useful for acquiring vibration information at low frequencies. They are suitable to measure shocks well above 100,000g.



pressure changes the resistance by mechanically deforming the sensor

Characteristics

- Frequency: Less than 1Hz 20kHz
- Limited temperature range: Calibration
- Light weight: Less than 1 to 10g
- AC/DC response
- Less than .01g to 200,000g





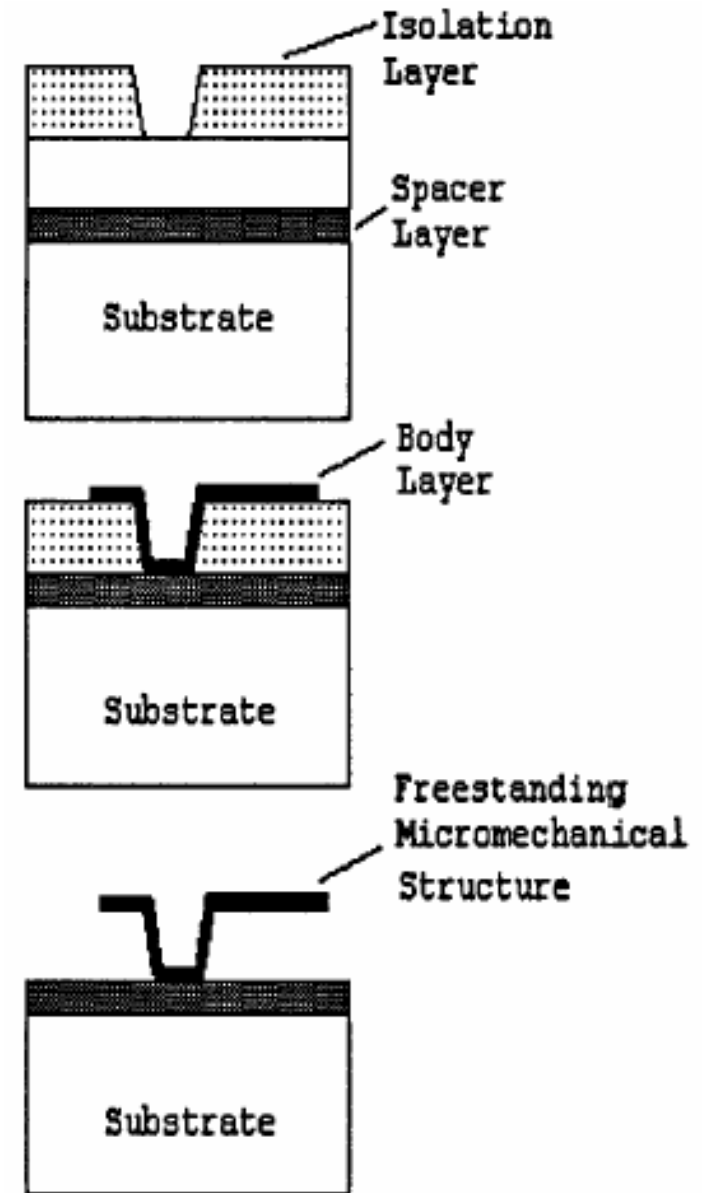
Inductive transducers

■ Linear variable differential transformers (LVDT)

- ☐ Higher natural frequencies
- ☐ Better resolution
 - Lower resistance to motion
- ☐ full scale range: $\pm 2 \text{ } 00 \text{ g}$,
- ☐ natural frequency: $35 \text{ } 620 \text{ Hz}$
- ☐ Nonlinearity: 1% of full scale
 - the full scale output is about 1 V with an LVDT excitation of 10 V at 2000 Hz,
- ☐ damping ratio 0.6 0.7
- ☐ residual voltage at null is less than 1%
- ☐ hysteresis less than 1% full scale
- ☐ size $\sim 50 \text{ mm}^3$

Micro-accelerometers

- By the end of the 1970s, it became apparent that the essentially planar processing IC (integrated circuit) technology could be modified to fabricate three-dimensional electromechanical structures, called micromachining.
- Accelerometers and pressure sensors were among the first IC sensors.
- The first accelerometer was developed in 1979.
- The selective etching of multiple layers of deposited thin films, or surface micromachining, allows movable microstructures to be fabricated on silicon wafers.
- structures are formed by polysilicon and a sacrificial material such as silicon dioxide.
- The sacrificial material acts as an intermediate spacer layer and is etched away to produce a free-standing structure.





Misura della velocità

- Metodi basati su un riferimento

- Misure effettuate sia sull'oggetto in movimento che su un riferimento

- Velocità media

$$v_{avg} = \frac{x_2 - x_1}{t_2 - t_1} = \frac{\Delta x}{\Delta t}$$

- Metodi inerziali

- Non richiedono il contatto con un riferimento

- Forniscono la velocità relativa alla velocità iniziale del sensore

$$v(t) = v_i + \int_{t_i}^t a(\tau) d\tau$$

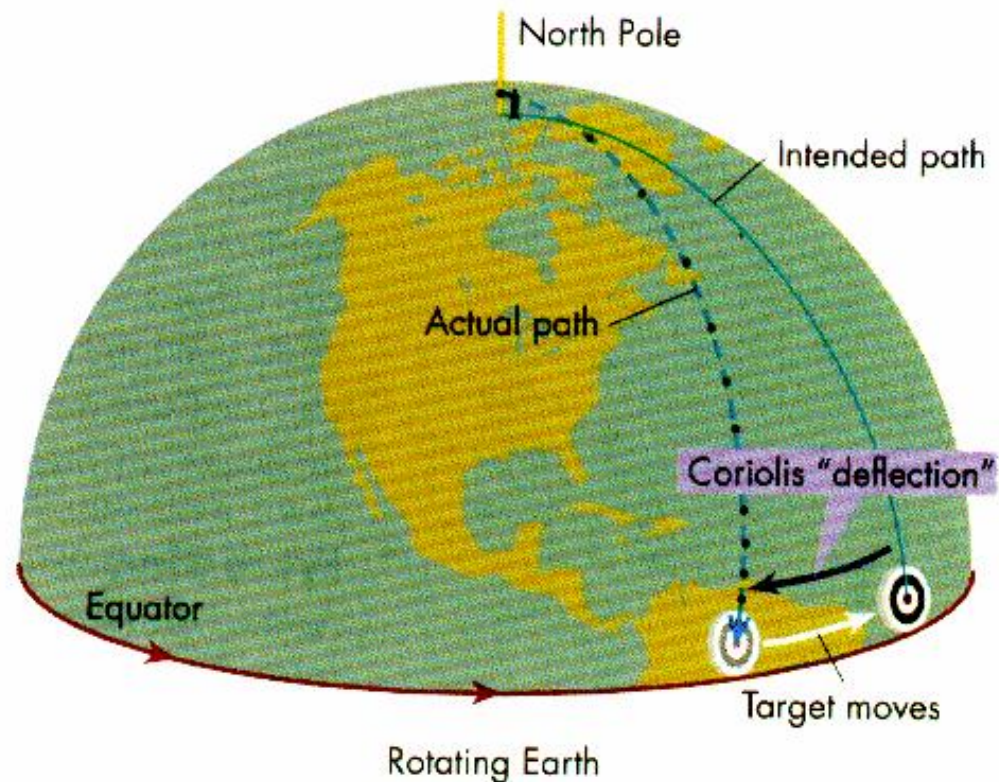


Misura della velocità angolare: giroscopi

Principi di funzionamento tipici dei giroscopi:

- ACCELERAZIONE DI CORIOLIS

Effetto Coriolis



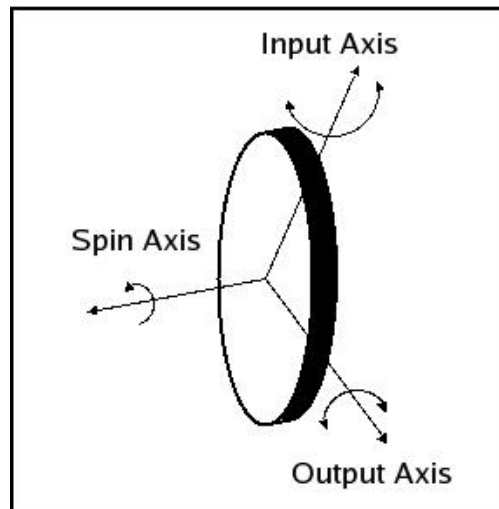
La formula matematica che esprime la **forza di Coriolis** è la seguente:

$$\vec{F}_C = 2m(\vec{v} \times \vec{\omega})$$

\vec{F}_C è la forza di Coriolis,
 m è la massa,
 \vec{v} è la velocità lineare,
 $\vec{\omega}$ è la velocità angolare del sistema in rotazione.

Giroscopi basati sul momento angolare

$$\tau = \frac{d\mathbf{L}}{dt} = \frac{d(I\omega)}{dt} = I\alpha$$



Se viene applicato un momento torcente τ perpendicolarmente all'asse di rotazione, quindi perpendicolare ad L , si sviluppa una forza perpendicolare sia a τ che ad L . Il moto che ne deriva è detto precessione. La velocità angolare del moto di precessione Ω_P , è data da:

$$\tau = \Omega_P \times \mathbf{L}$$

dove:

il vettore τ è il momento torcente

il vettore L è il momento angolare

il valore scalare I è il momento di inerzia

il vettore ω è la velocità angolare

il vettore α è l'accelerazione angolare

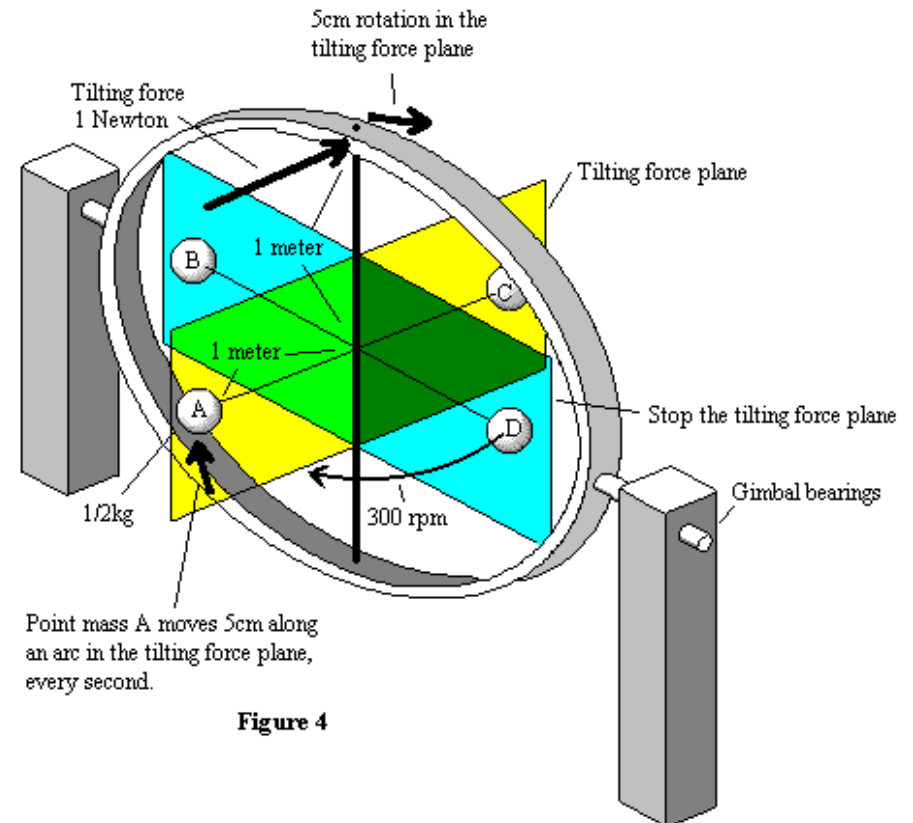


Figure 4

Giroscopi basati sull'accelerazione di Coriolis

Vibrating mass gyroscopes

A vibrating element (vibrating resonator) creates an oscillatory linear velocity

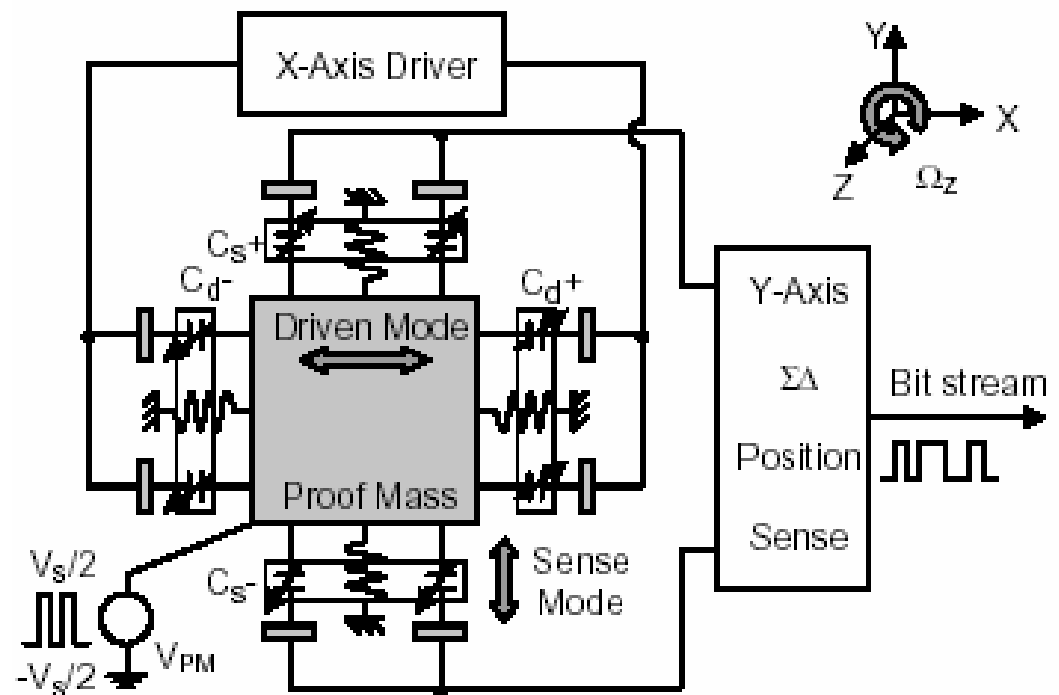
If the sensor is rotated about an axis orthogonal to this velocity, a Coriolis acceleration is induced

The vibrating element is subjected to the Coriolis effect that causes secondary vibration orthogonal to the original vibrating direction.

By sensing the secondary vibration, the *rate of turn* can be detected.

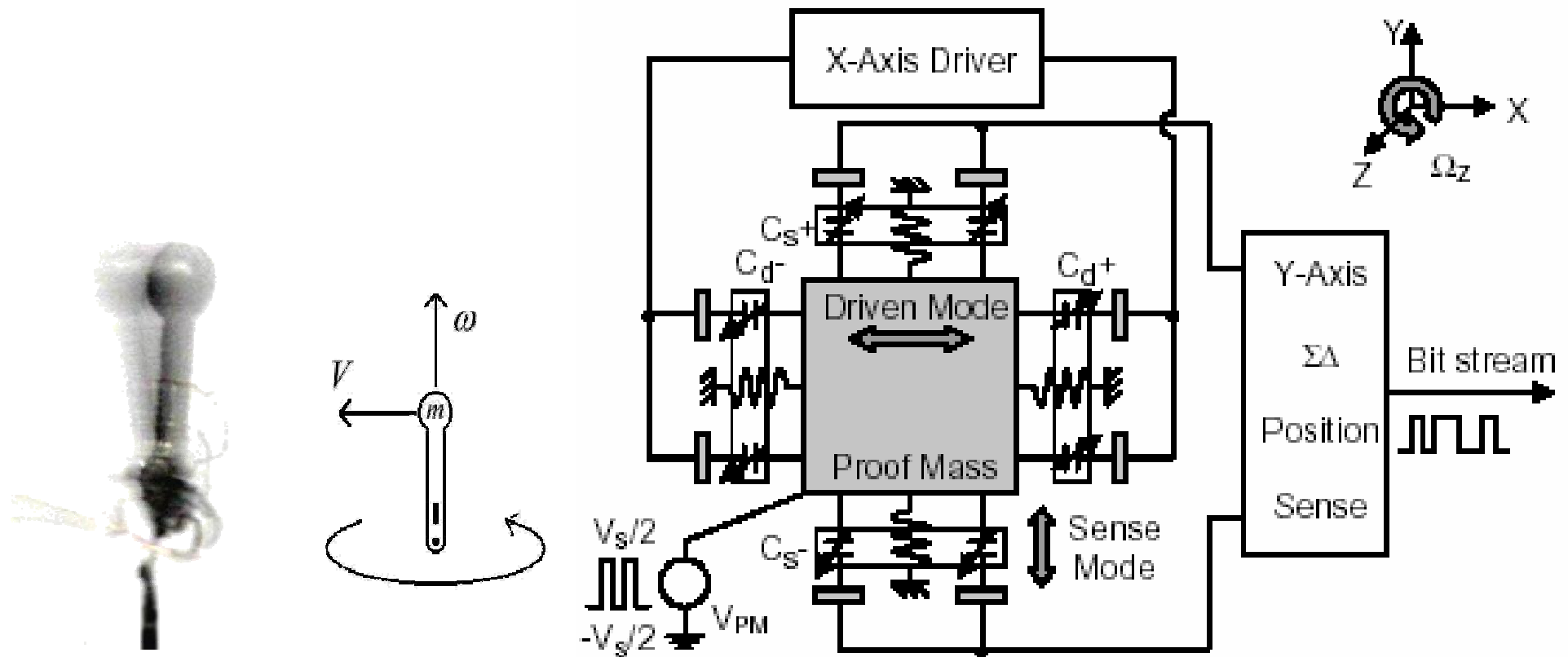
The Coriolis force is given

by: $\mathbf{F}_C = -2m(\boldsymbol{\omega} \times \mathbf{v})$



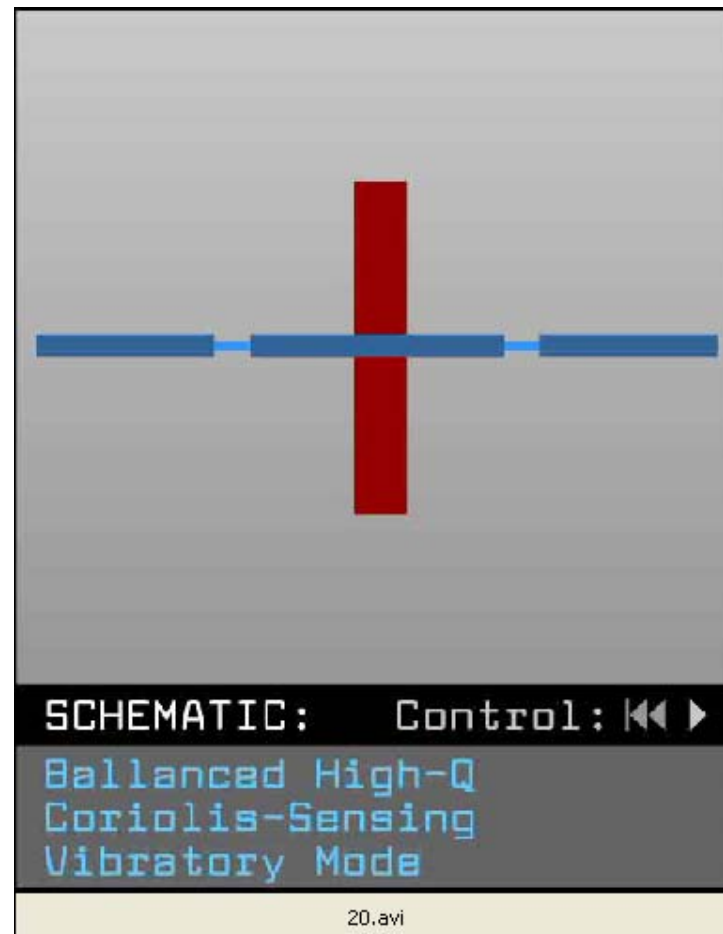
■ Gyroscopes

- Coriolis' force detection



Giroscopi basati sull'accelerazione di Coriolis

The most common design technology for these sensors has generally used a stable quartz resonator with piezoelectric driver circuits.



Progettazione di un sistema vestibolare per una testa robotica





Sintesi delle funzionalità del sistema vestibolare umano

- Accelerazioni lineari
- Velocità angolari
- Range: ...
- Risoluzione: ...



Functional specifications for the artificial vestibular system

From a functional point of view, the human vestibular system provides:

- linear acceleration
 - angular velocity
- of a rigid body (the head) in a 3D space

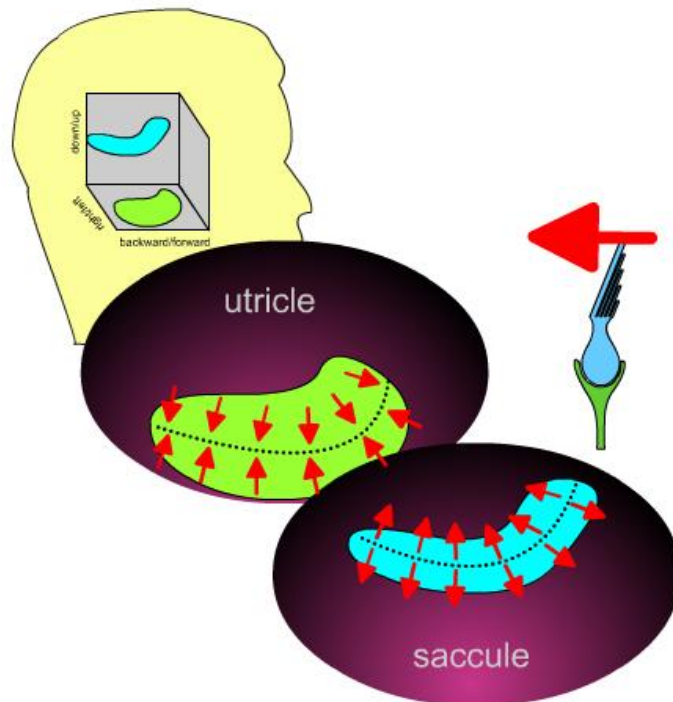
A biologically inspired artificial vestibular system has to be able to detect:

- angular velocity in 3-orthogonal directions,
- direction and magnitude of gravity,
- transient linear accelerations due to head motion



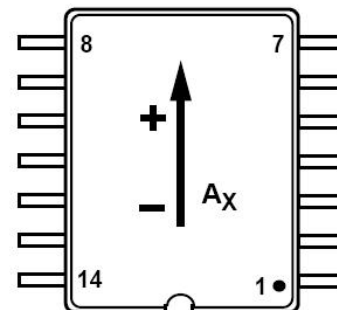
- Pitch, Roll and Yaw angular velocity
- Direction and magnitude of gravity
- X, Y and Z-direction transient acceleration

Artificial Vestibular System



As well as the Human Vestibular System does, the Artificial Vestibular System has to be able to detect angular velocity in 3-orthogonal directions of the head and **direction and magnitude of gravity**, as well as **transient linear acceleration** due to movement.

Acceleration detector:
Accelerometer

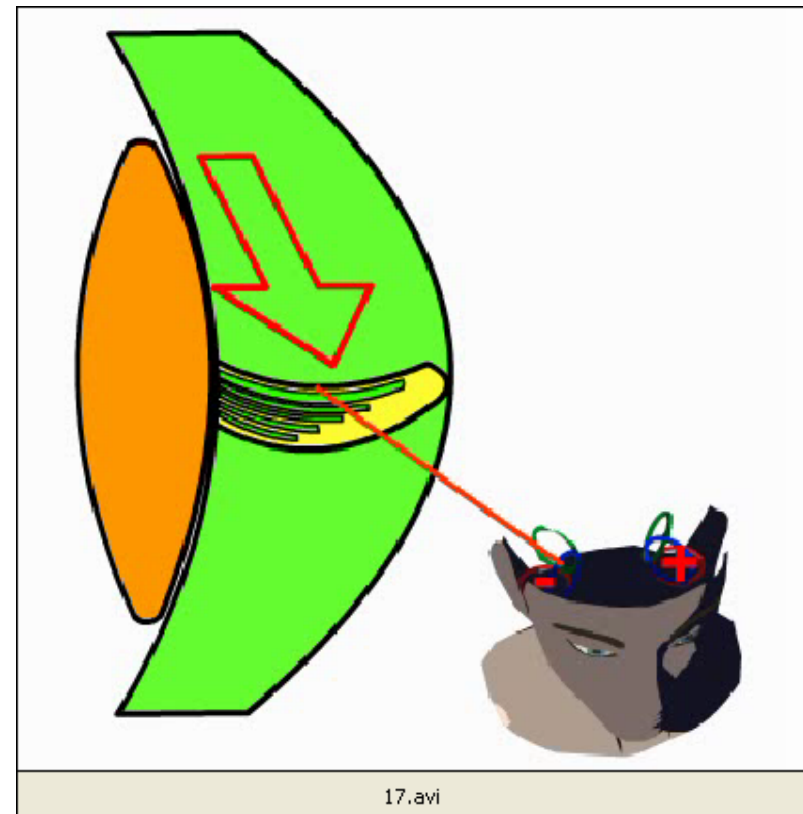


Artificial Vestibular System

As well as the Human Vestibular System does, the Artificial Vestibular System has to be able to detect **angular velocity in 3-orthogonal directions** of the head and direction and magnitude of gravity, as well as transient linear acceleration due to movement.

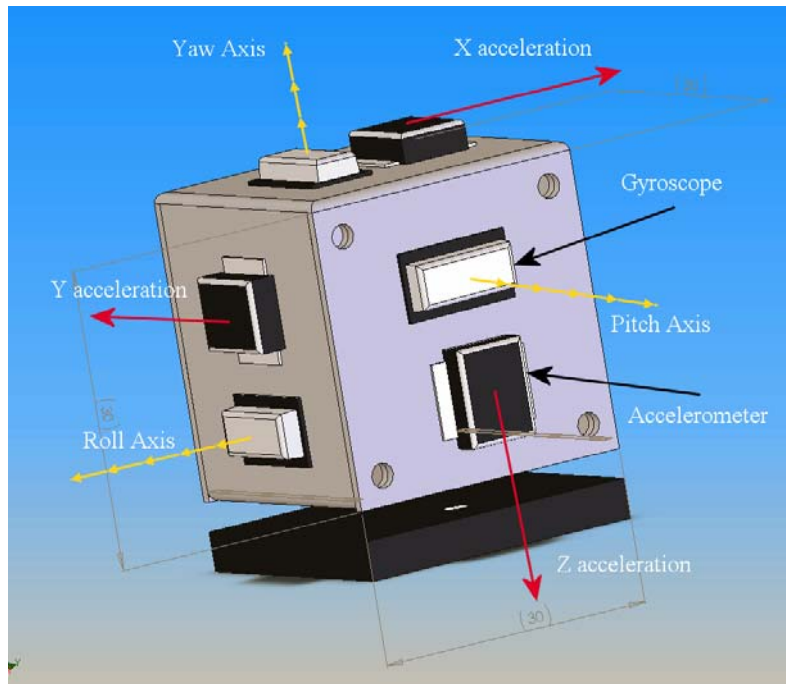


Angular velocity
detector: Gyroscope



Artificial Vestibular System I

Accelerometers can play the role of the otholitic organs,
Gyroscopes can play the role of the semicircular canals



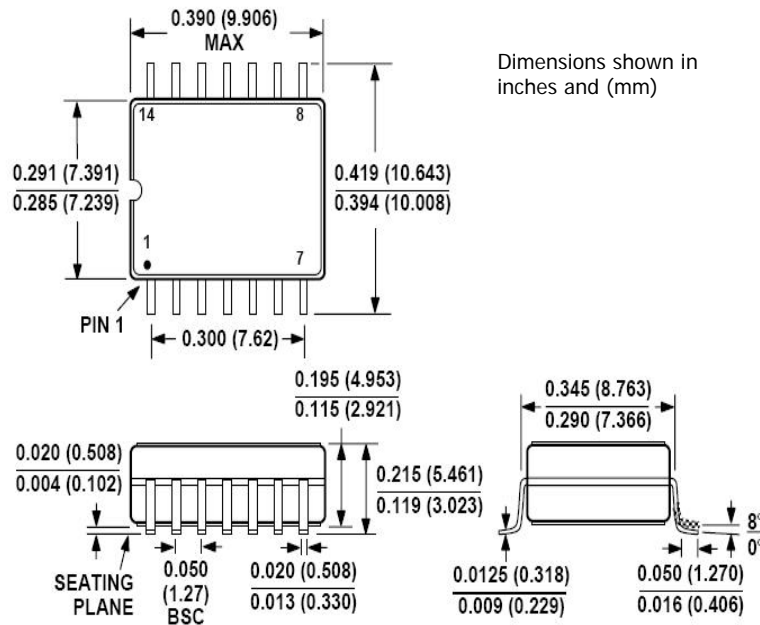
3 mono-axial Piezoelectric
Vibrating Gyroscopes

3 mono-axial accelerometers

In order to obtain a 3-axial inertial sensor system, these six devices are mounted on three orthogonal surface of a few-millimeter-sized cubic mass

Accelerometer Features

ADXL150 Single Axis ImemS Accelerometers by ANALOG DEVICES



Parameter	Conditions	Units
SENSOR Guaranteed Full-Scale Range	Min ± 40 , Max ± 50	g
Sensitivity	Min 33.0 Typ 38.0 Max 43.0	mV/ g
Frequency Response -3 dB Bandwidth	Min 900, Max 1000	Hz
Power Supply (Vs) Functional Voltage Range Quiescent Supply Current	Min 4.0 Max 6.0 Typ 1.8 Max 3.0	V mA

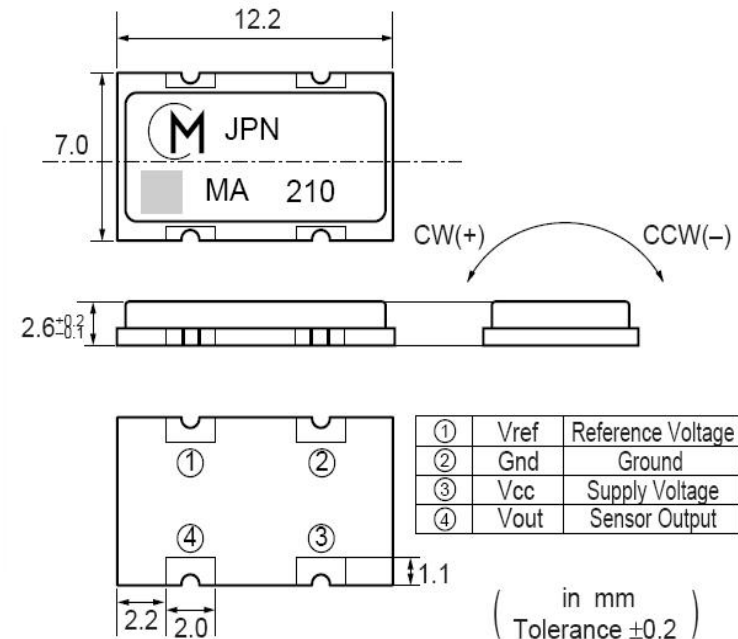
The ADXL150 is third generation $\pm 50 g$ surface micromachined accelerometers. It offers lower noise, wider dynamic range, reduced power consumption and improved zero g bias drift. Thanks to its features, this device is particularly appropriate for detecting head accelerations involved in gaze position control and tracking of the objects.

Gyroscope Features

Piezoelectric Vibrating Gyroscopes by Murata

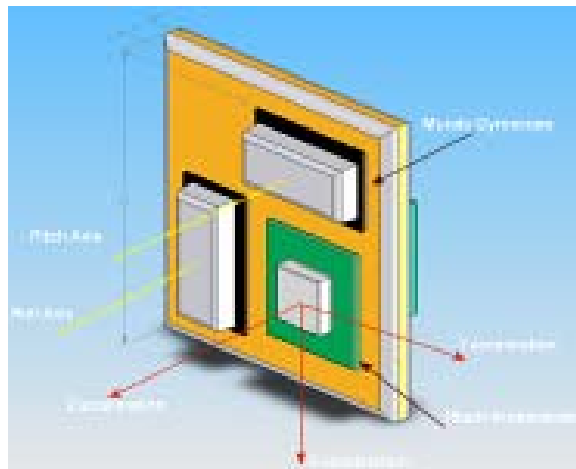
This product is an angular velocity sensor that uses the phenomenon of Coriolis force and achieve an ultra-small size of about 0.2cc. Its small and lightweight shape increase flexibility of installment and let the apparatus to be downsized.

Thanks to its features, this device is particularly appropriate for detecting head angular velocities involved in gaze position control and tracking of the objects.

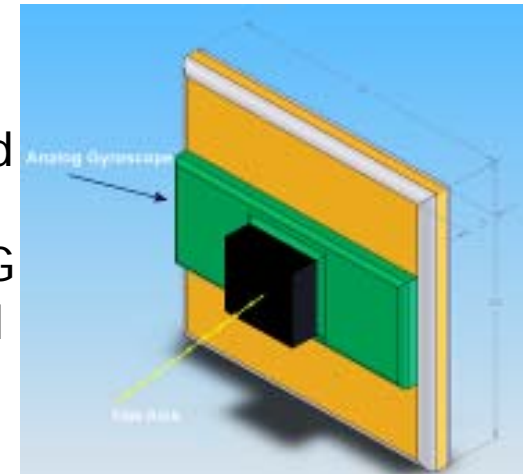


Supply Voltage (Vdc)	Maximum Angular Velocity (deg./sec.)	Output (at Angular Velocity=0) (Vdc)	Scale Factor (mV/deg./sec.)	Response (Hz)	Weight (g)
2.7-5.25	+/-300	1.35	0.67	50 max.	0.4

Second Prototype



The Gyroscopes by muRata are used for angular velocity detection around the Pitch and the Roll axis, while the mono-axial gyroscope ADXRS300ABG by Analog Device is employed for detecting the angular velocity around the Yaw axis.



The introduction of the ultrasmall tri-axial accelerometer module H48C by Hitachi allows a strong reduction of the total system size.

The new prototype of the artificial vestibular system will be smaller and lighter than the previous model

The ADXRS300ABG measures the angular velocity around an axis orthogonal to its mounting surface. In this way, all the 3 gyroscopes can be integrated on a single plane.

Second Prototype

Hitachi H48C 3-axis acceleration

- (1) Compact and slim (world's thinnest)
Package size: $4.8 \times 4.8 \times 1.3$ mm.
- (2) High detection sensitivity (1.5 times greater than earlier sensors)
Triaxial, analog, simultaneous output sensors with sensitivity increased from 333mV/G to 500mV/G.
- (3) Low power consumption (2/3 that of earlier sensors)
Low current drain of 3V/0.4mA when operating.



3. Specifications

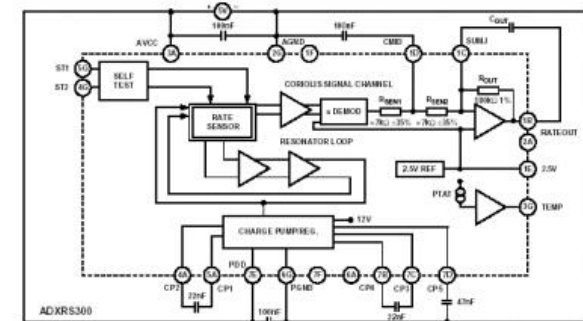
	Unit	Standard products	Newly developed sensor	Remarks
Package size	mm	4.8×4.8	4.8×4.8	
Package thickness	mm	1.5	1.3	
Acceleration detection range	G	± 3	± 2	
Power-source voltage	V	2.2 to 3.6	2.2 to 3.6	
Current drain	mA	0.6	0.4	Power source voltage 3V
Detection sensitivity	mV/G	333	500	Power source voltage 3V
Shock durability	G	5000	5000	Duration of action: 0.2ms

Analog Device Yaw rate Gyroscope

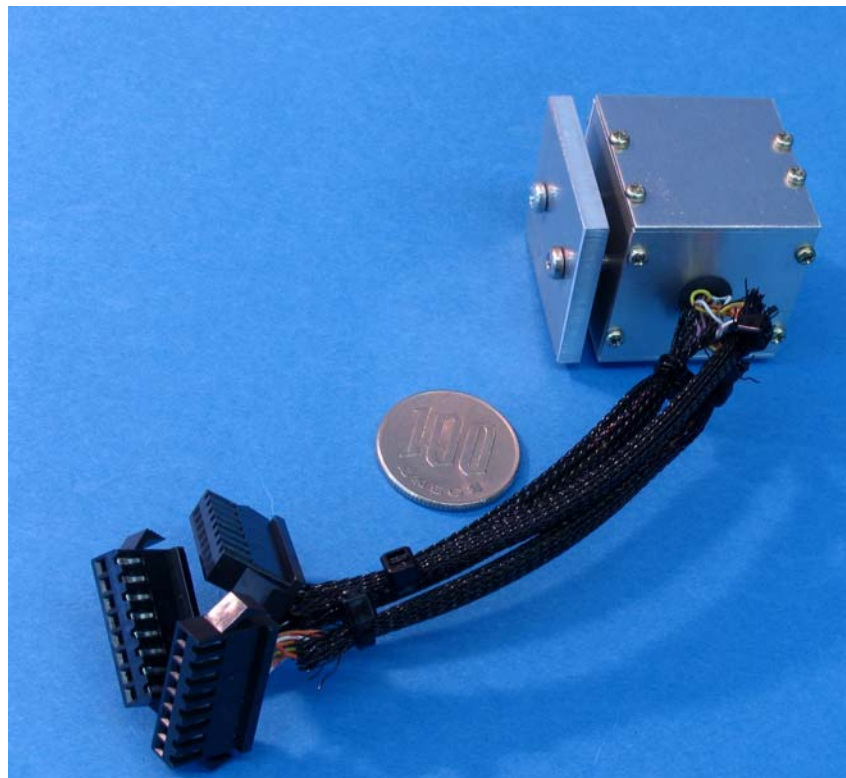
- Complete rate gyroscope on a single chip
- Z-axis (yaw rate) response
- High vibration rejection over wide frequency
- 2000 g powered shock operation
- Self-test on digital command
- Temperature sensor output
- Precision voltage reference output
- Absolute rate output for precision applications
- 5 V single-supply operation
- Ultrasmall and light (<0.15 cc, <0.5 gram)

Specifications	
Range	$\pm 1 - 300$ °/s
Sensitivity	5mV/°/s
Bandwidth	0.04kHz
Noise Density (°/s/√Hz)	0.1
Nonlinearity	0.1% of FS
Temp Sensor	Yes
Voltage Reference	Yes
Supply Voltage	4.75 to 5.25
Supply Current	6mA
Temp Range	-40 to 85°C
Package	32-BGA

Functional Block Diagram



Artificial Vestibular System II



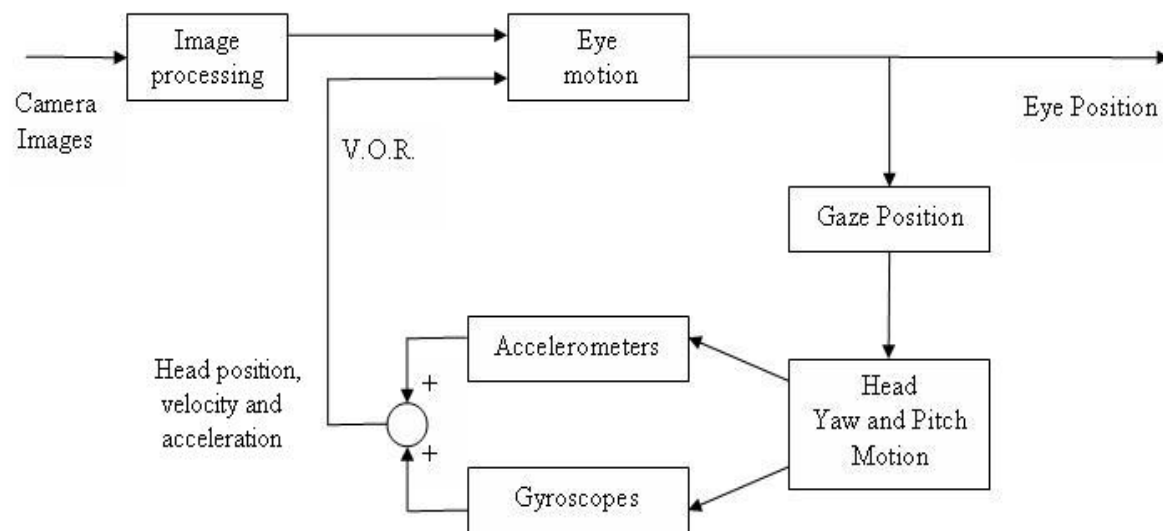
Data coming from the six devices need to be further processed and integrated in order to calculate orientation and position of the head during motion

- Orientation is estimated from the angular velocity sensor signals by integration
- The resulting head orientation as a function of time can be subsequently used to express the 3D accelerometer signals in inertial coordinates using a coordinate transformation

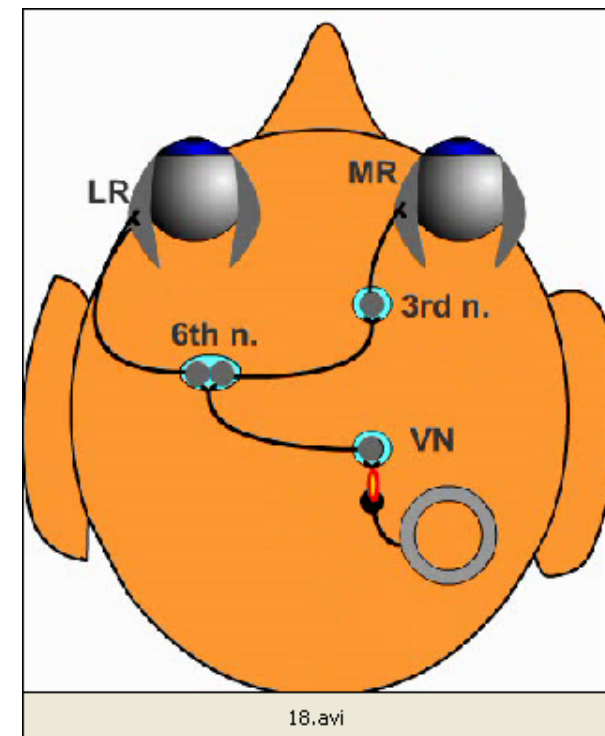
An accurate estimation of accelerations in 3D-space supposes fusing information of the accelerometers and angular velocity sensors

Outline of the artificial vestibulo-ocular reflexes

Artificial Vestibulo-ocular Reflex

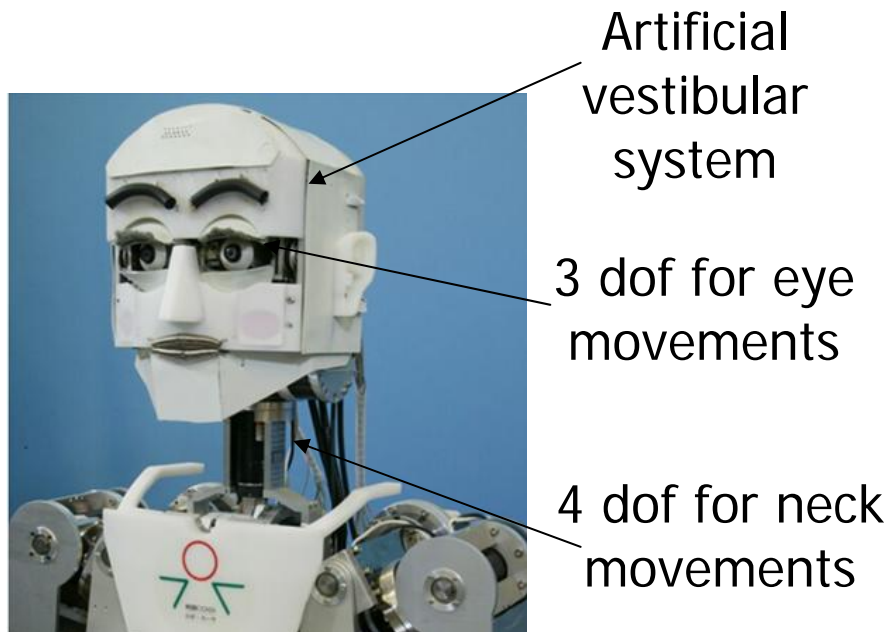


Human Vestibulo-ocular Reflex



Experimental tests in detecting robotic head motion

WE-4RII

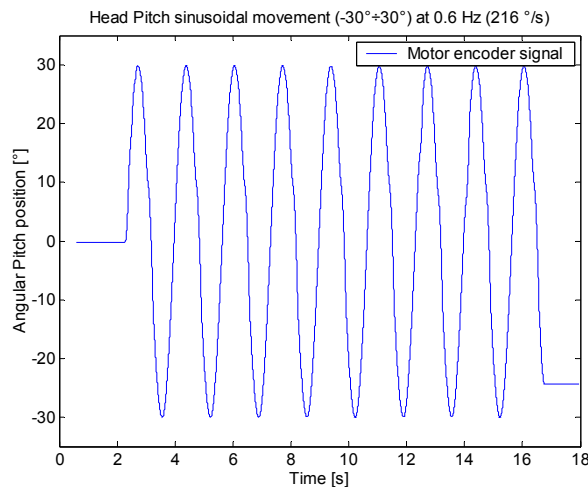


- Impose movements to head (neck):
 - ☐ Upper pitch
 - ☐ Roll
 - ☐ Yaw
- Record the encoder signal
- Record the vestibular system signal
- Compare the two signals

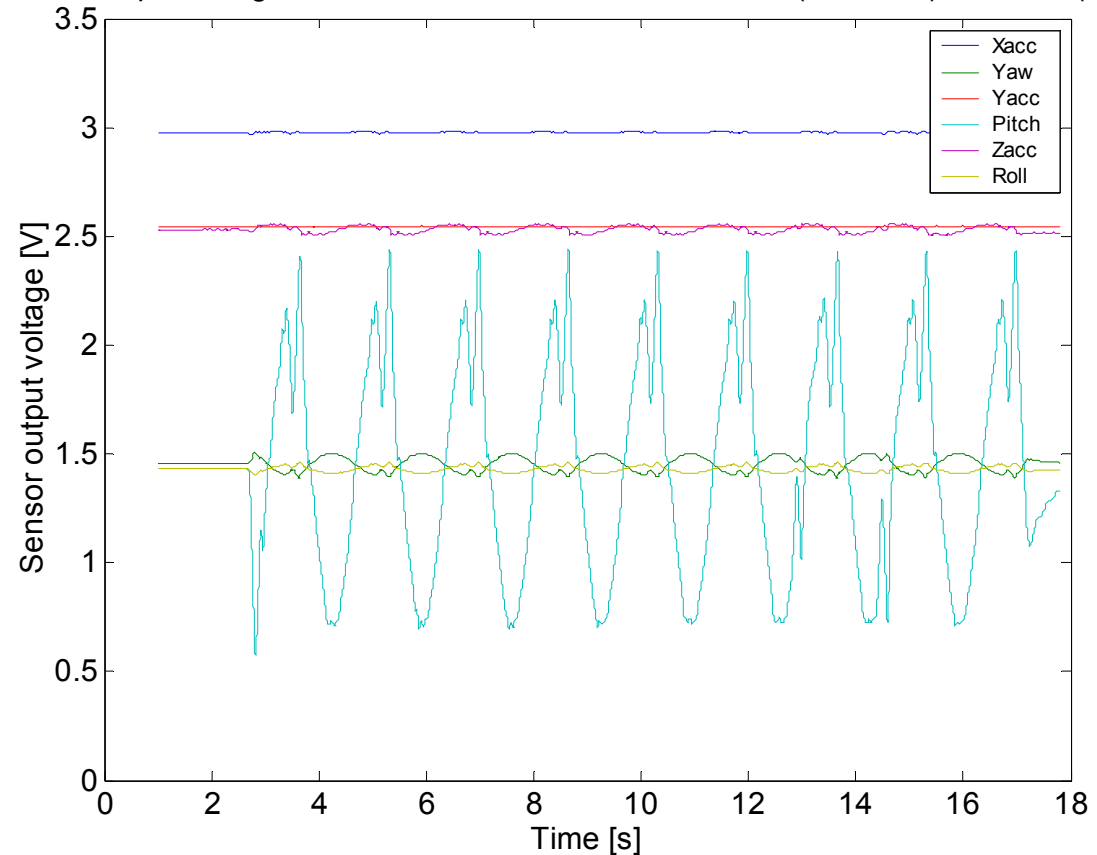
Experimental results in the detection of the WE-4RII robotic head motion

Upper Pitch

Good correlation, in terms of frequency response
Most significant signal from the gyro around the pitch axis
Largest variation from the accelerometer along the Z-direction, in relation to gravity



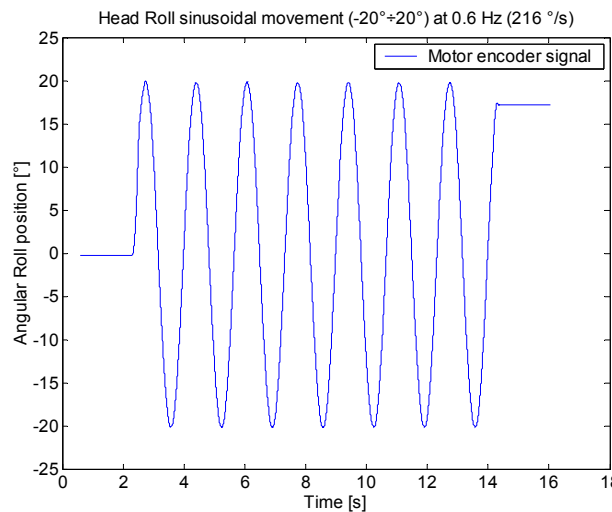
Sensor output voltage for Head Pitch sinusoidal movement ($-30^\circ \div 30^\circ$) at 0.6 Hz (216°/s)



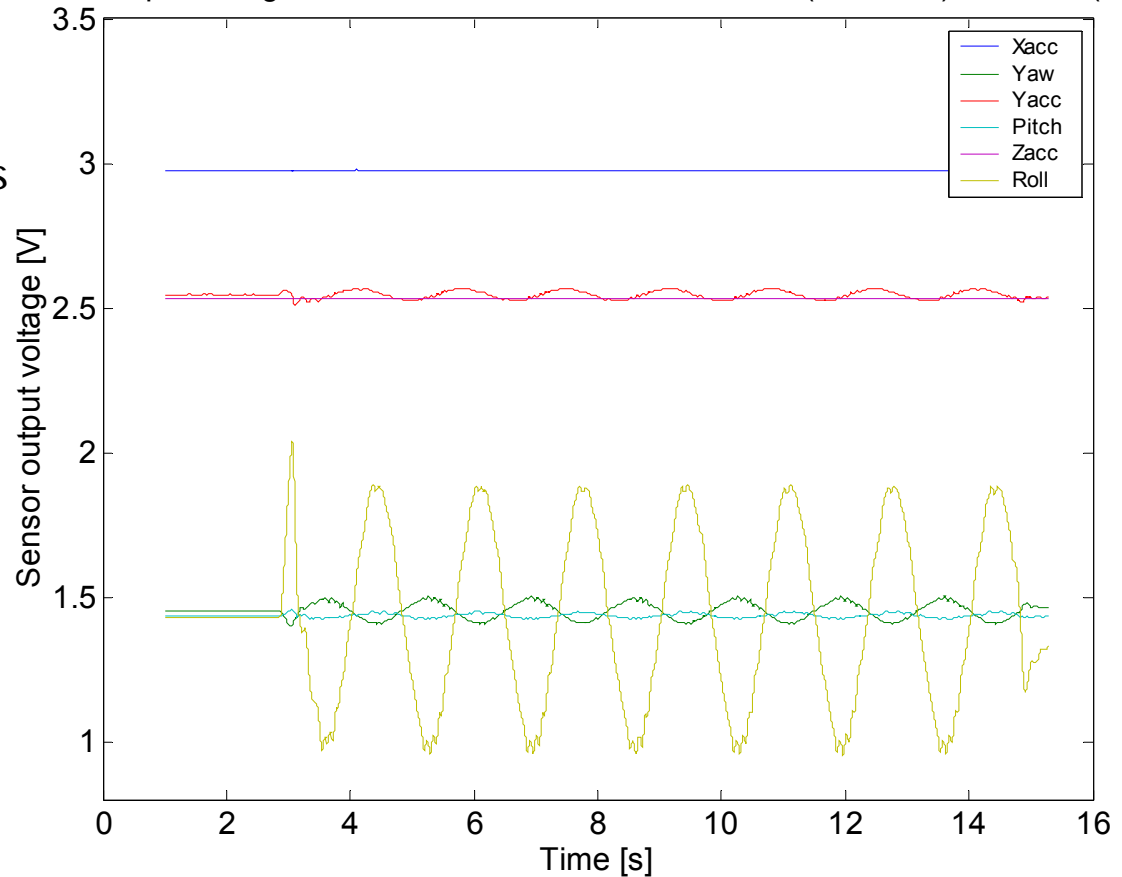
Experimental results in the detection of the WE-4RII robotic head motion

Roll

Roll gyro sensor output in phase with the motor encoder signal
The accelerometer along the Y-direction detected the variation of its sensitive axis in relation to gravity



Sensor output voltage for Head Roll sinusoidal movement ($-30^{\circ}+30^{\circ}$) at 0.6 Hz (216 $^{\circ}$ /s)

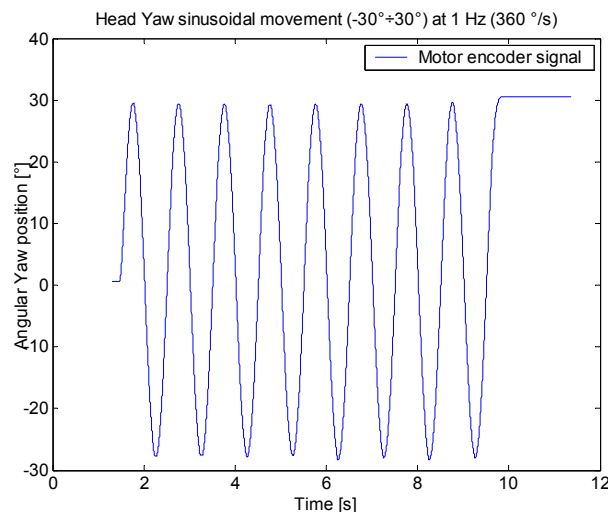


Experimental results in the detection of the WE-4RII robotic head motion

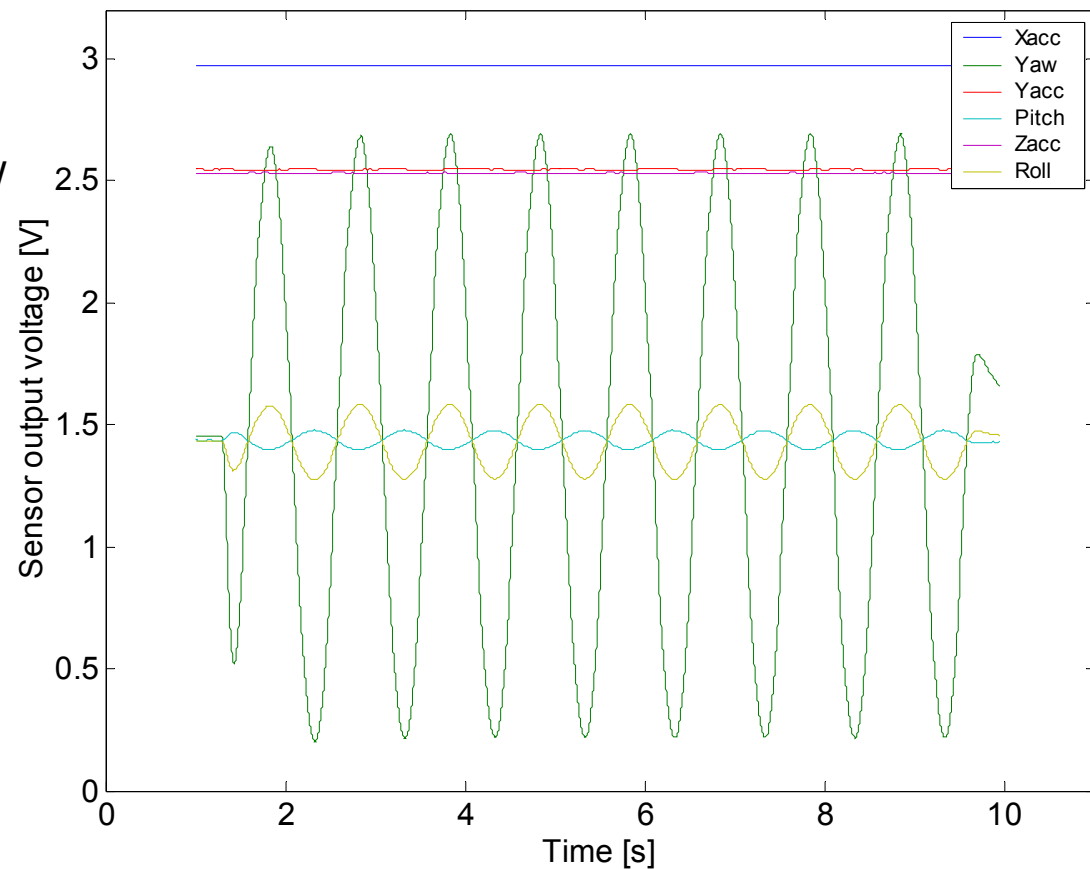
Yaw

Smoother and clearer sensor output signals (no movement obstruction by wires, causing vibration during the upper pitch and roll movements)

All accelerometers silent

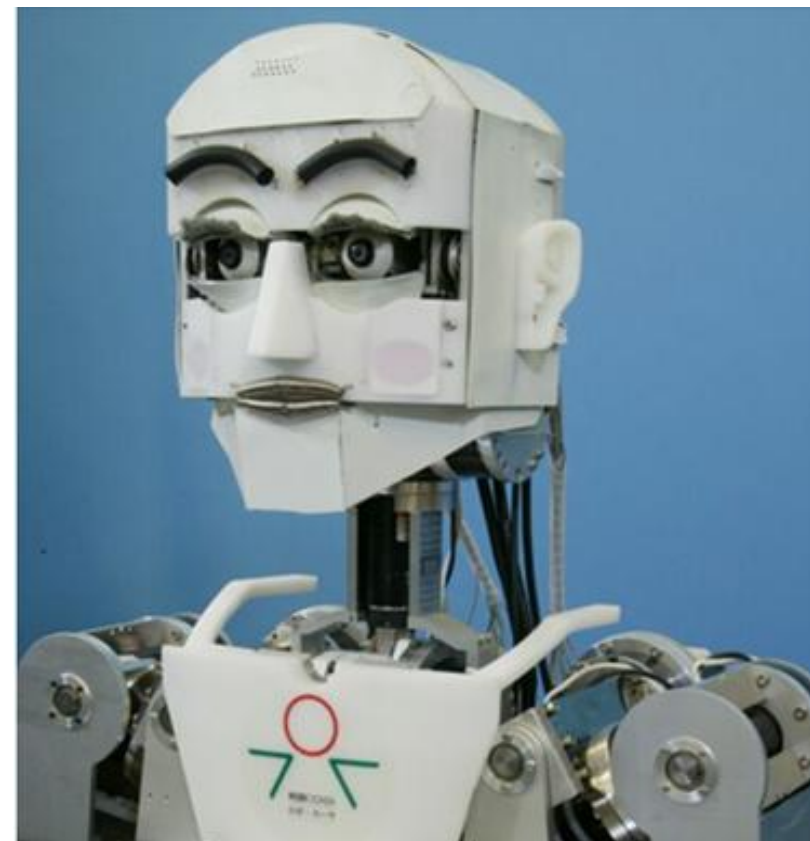
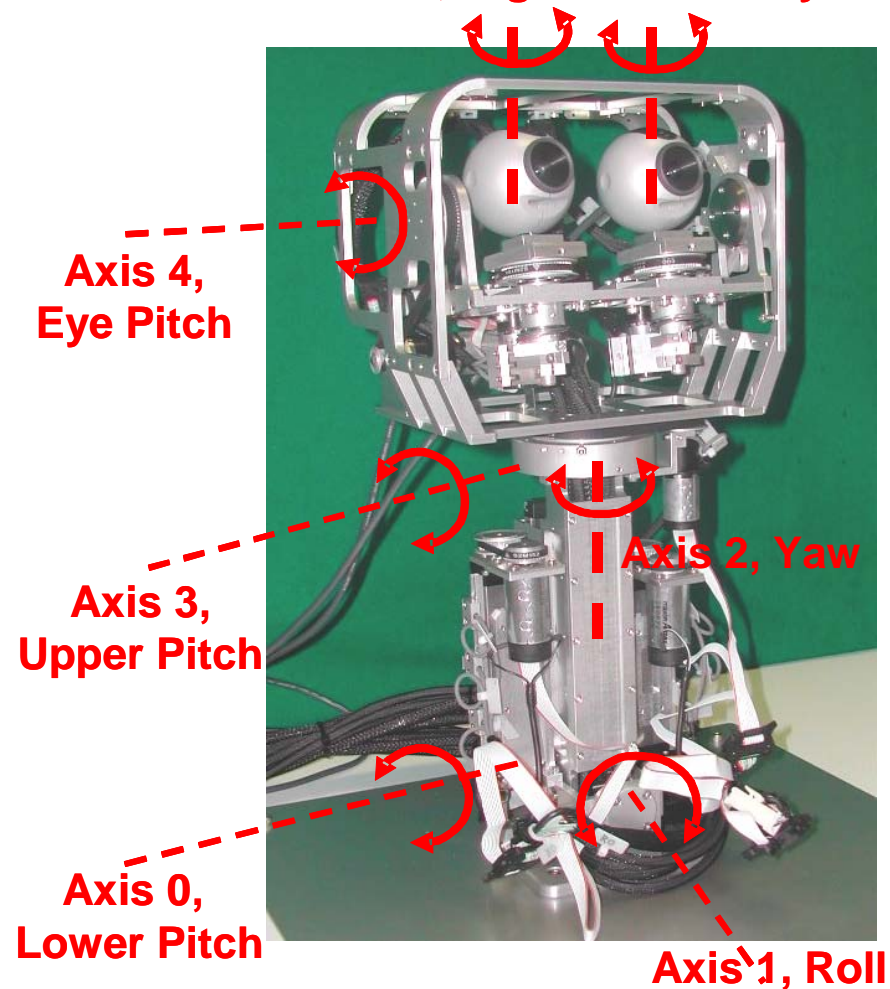


Sensor output voltage for Head Yaw sinusoidal movement ($-30^\circ \div 30^\circ$) at 1 Hz ($360^\circ/\text{s}$)

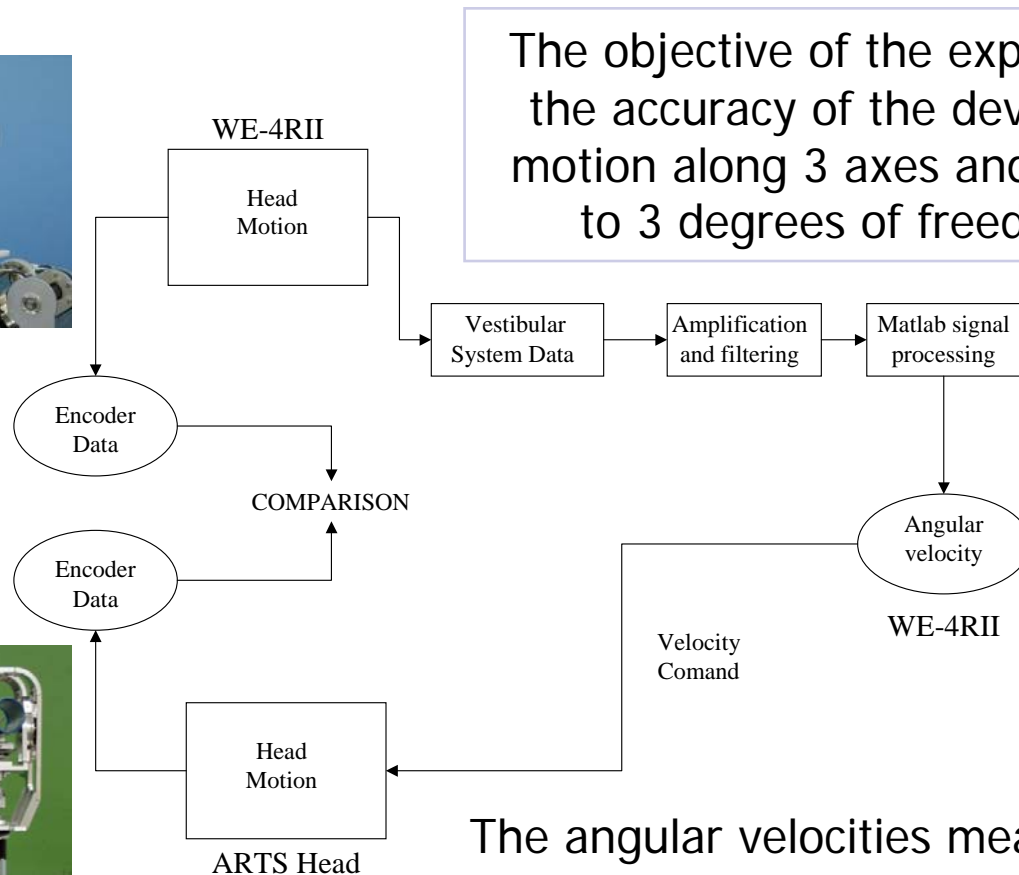


Experimental validation with two Robotic Heads

Axes 5 and 6, Right and Left Eye Pitch



Validation Experiments

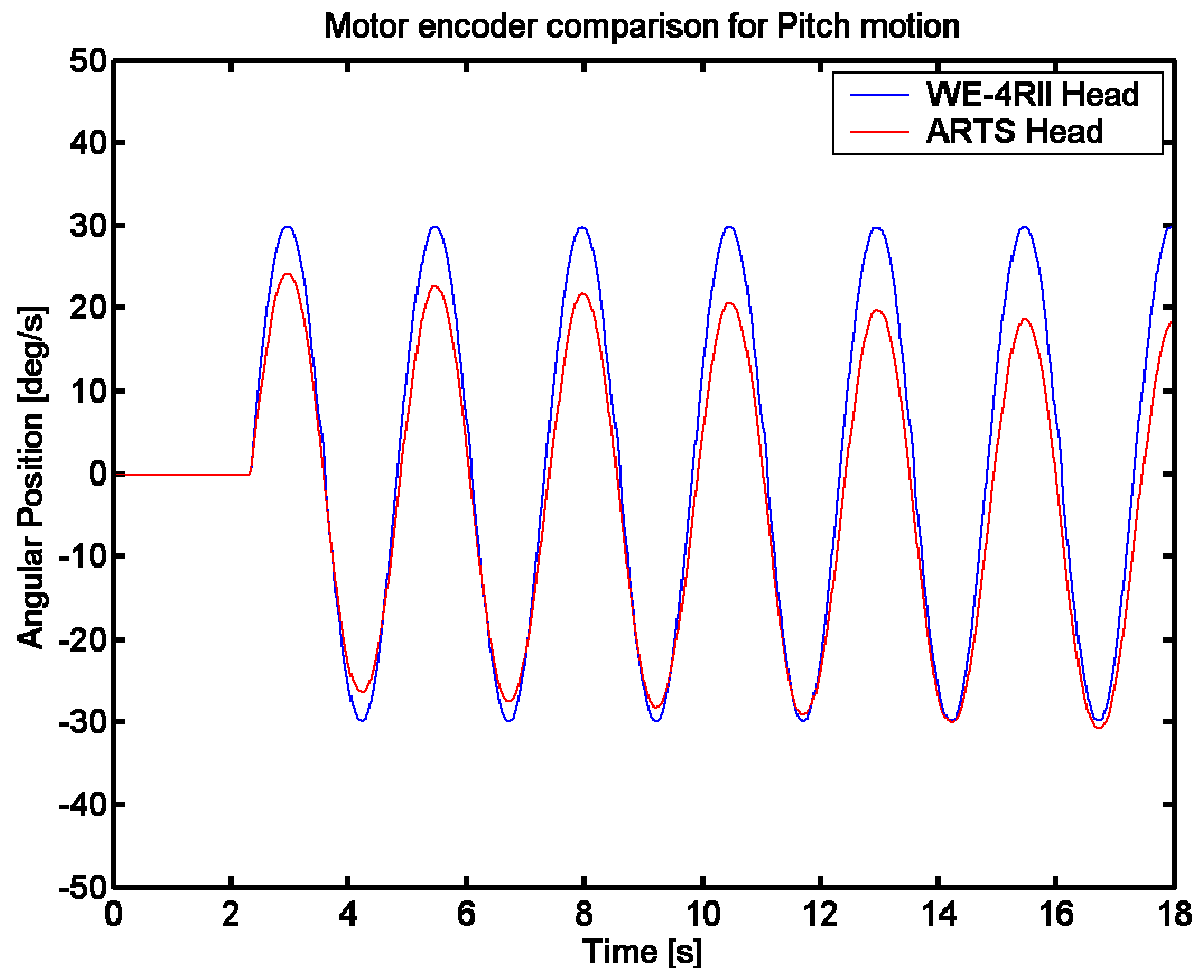


The objective of the experiments is to investigate the accuracy of the developed system to detect motion along 3 axes and to transmit such motion to 3 degrees of freedom of a robotic head.

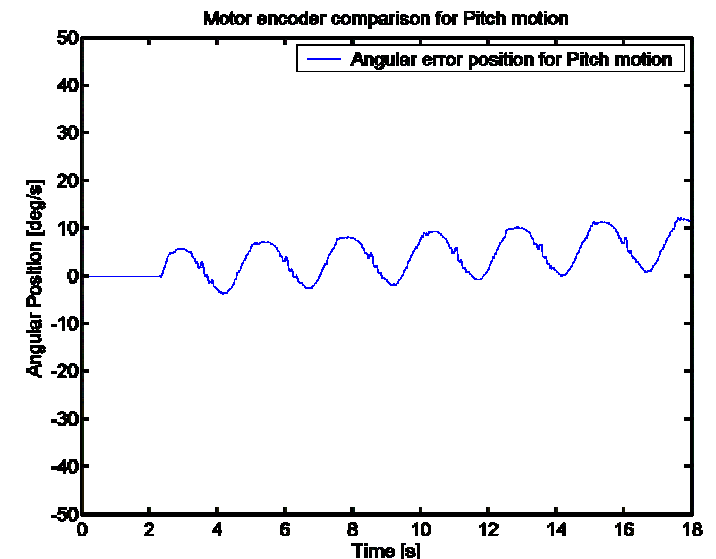
The artificial vestibular system was integrated on the WE-4RII robotic platform and the measured sensory data were used as an external command for the ARTS robotic platform.

The angular velocities measured by the artificial system were used as external input commands for the ARTS robotic head, directly in **velocity domain**, overcoming all the artifices due to the numerical integration of system outputs.

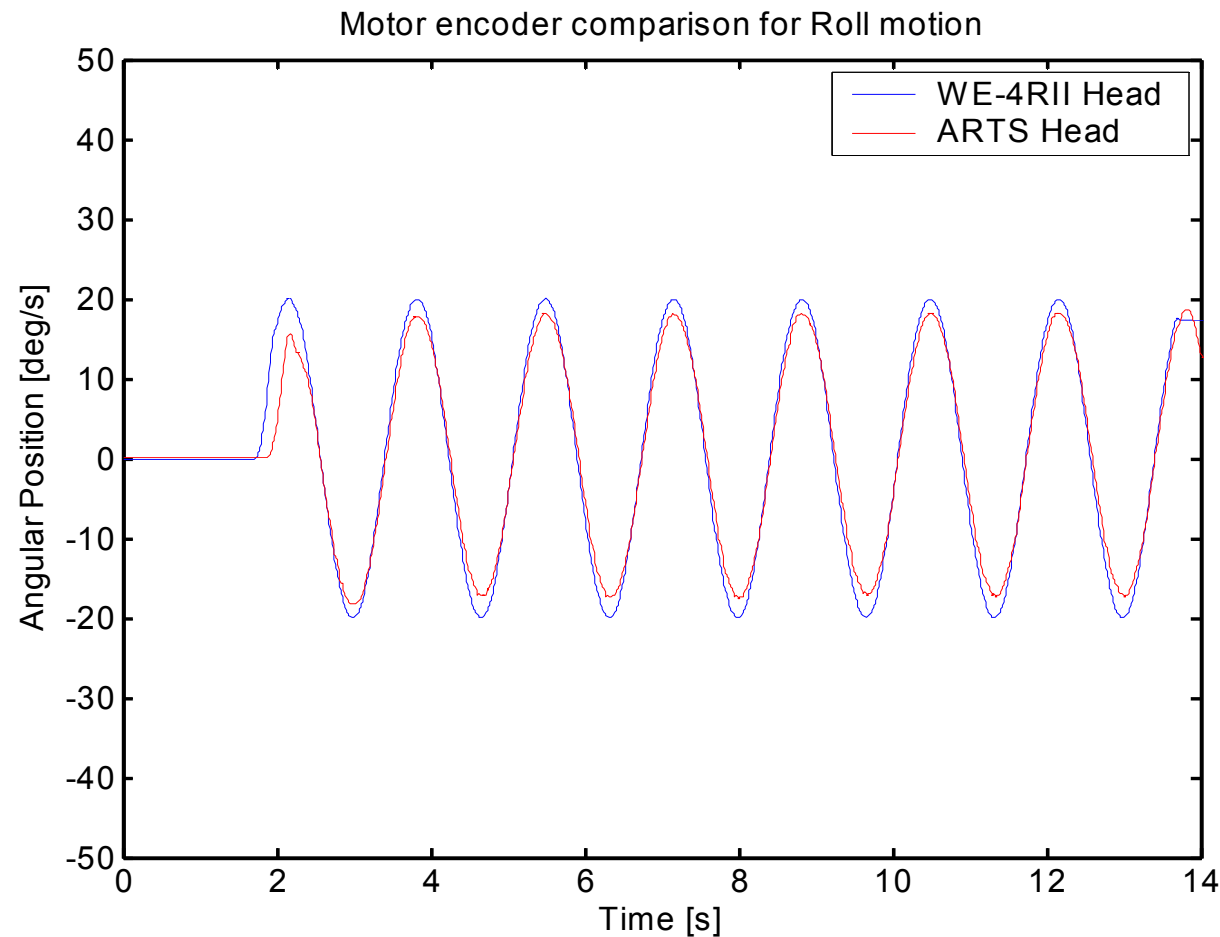
Motor encoder comparison for Upper Pitch movements



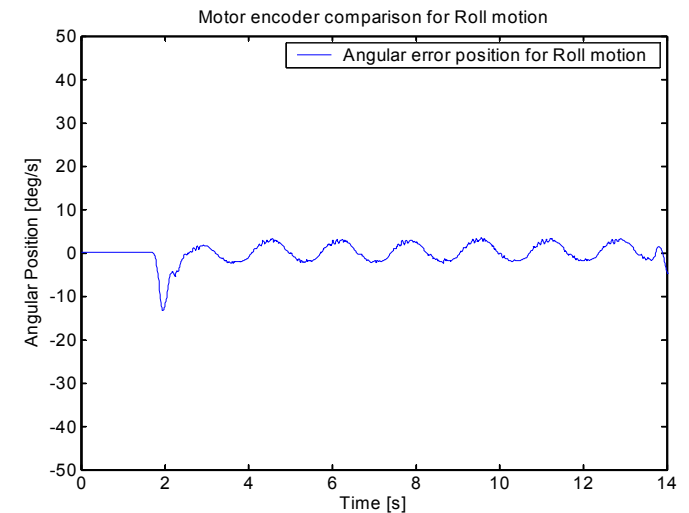
Angular error position
during Upper Pitch
movements



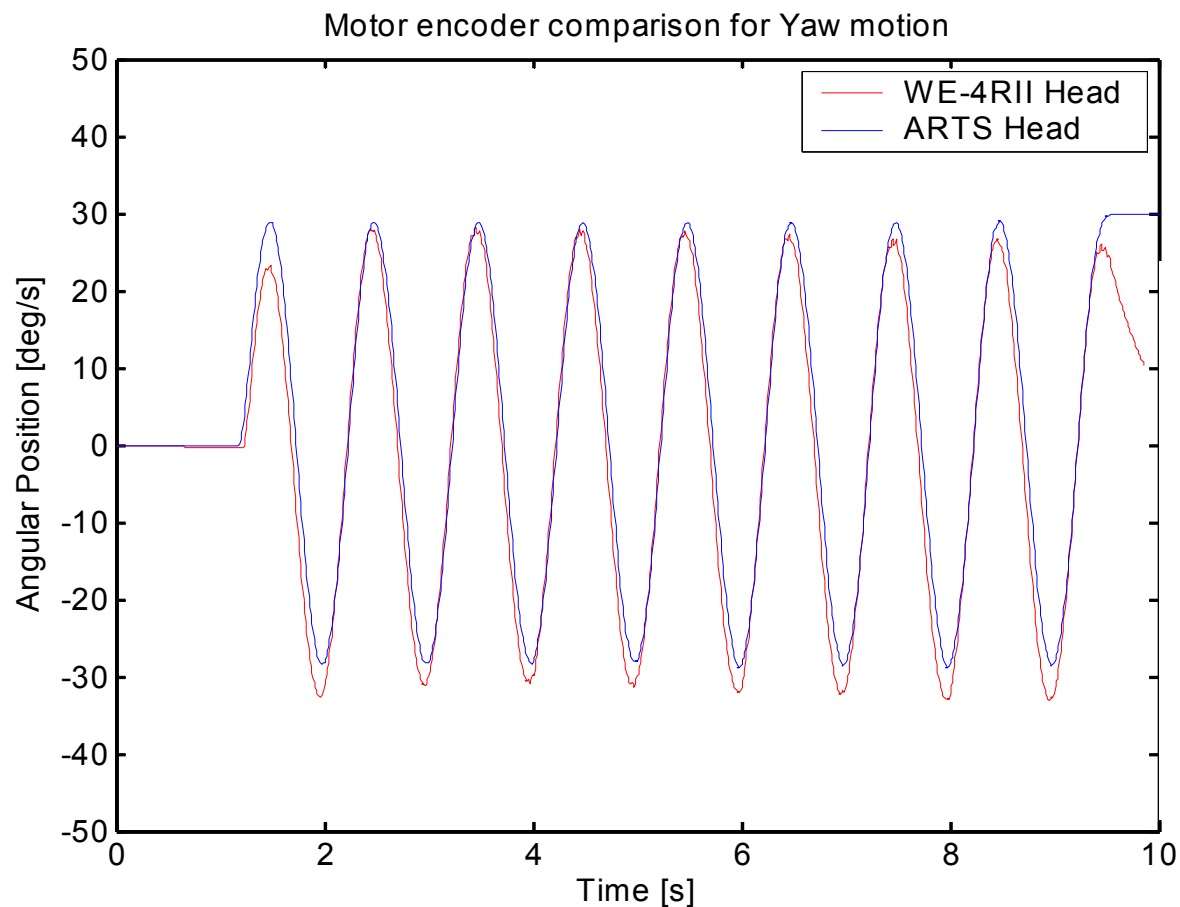
Motor encoder comparison for Roll movements



Angular error position during Roll movements



Motor encoder comparison for Yaw movements



Angular error position during Yaw movements

