

# Corso di Percezione Robotica (PRo)

## Modulo C. Percezione Attiva

### Percezione vestibolare

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# Sommario della lezione

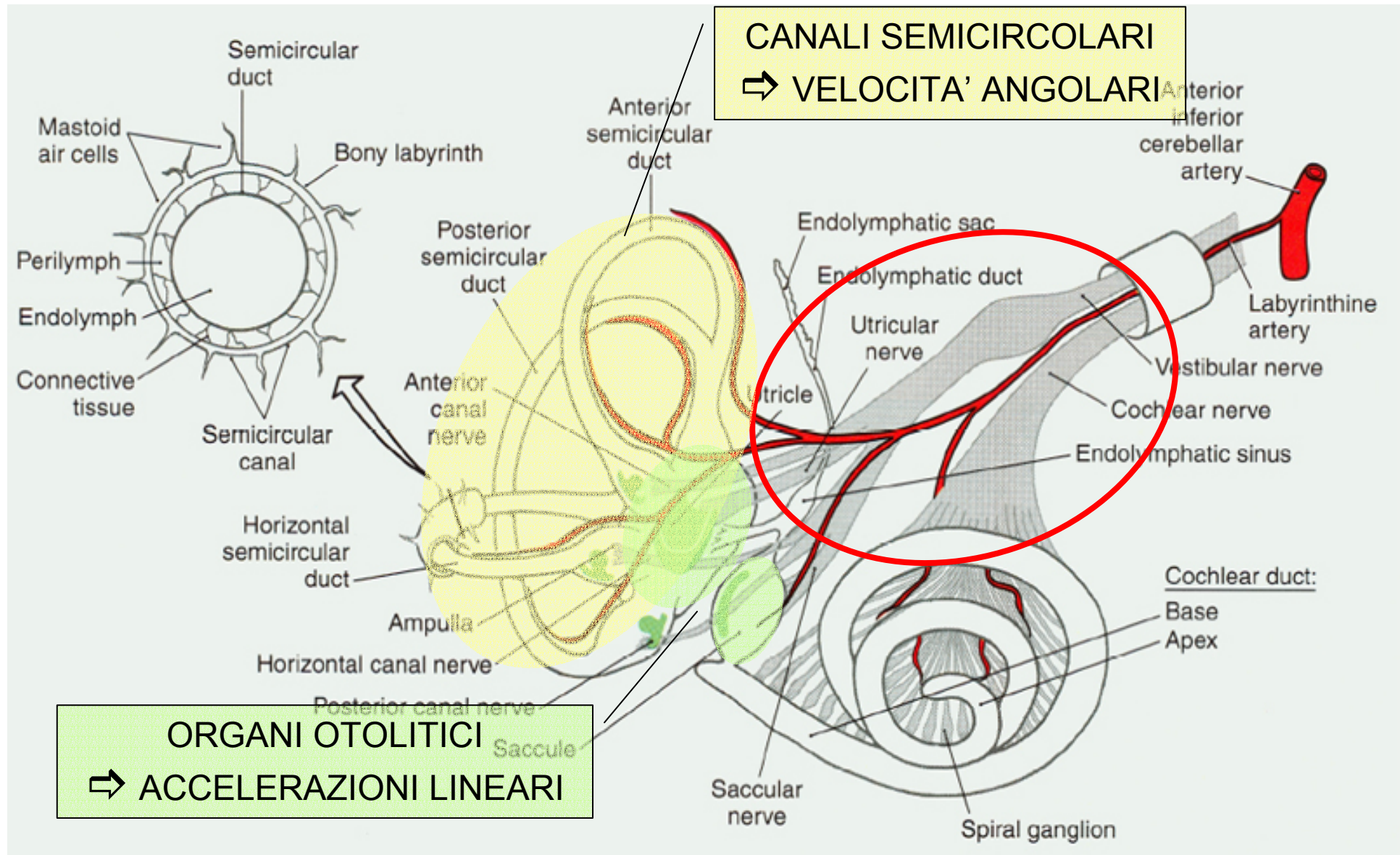
- Il sistema vestibolare nell'Uomo:
  - Funzioni e ruolo del sistema vestibolare nell'Uomo
  - Anatomia e neurofisiologia del sistema vestibolare
- Sistemi vestibolari artificiali
  - Dispositivi sensoriali funzionalmente analoghi:
    - accelerometri
    - giroscopi
- Possibili applicazioni dei sistemi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

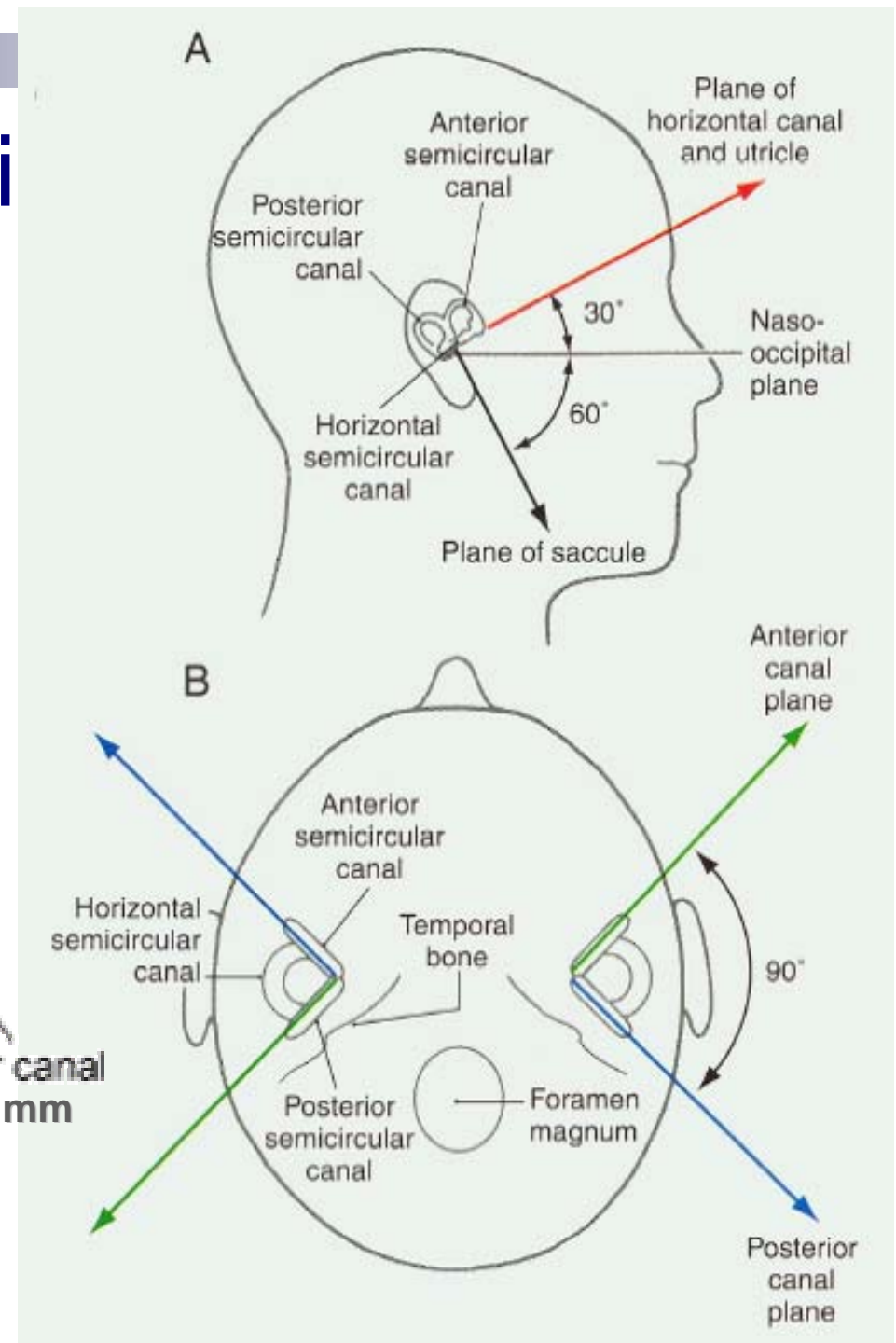
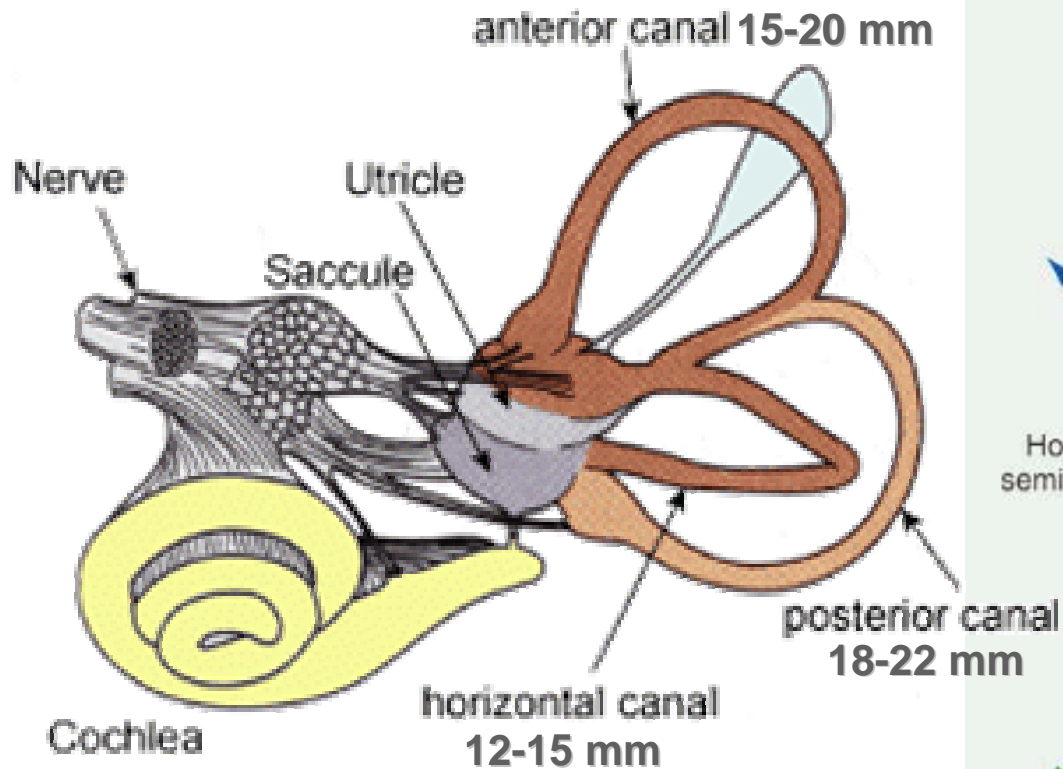
# Il sistema vestibolare umano





# I canali semicircolari

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

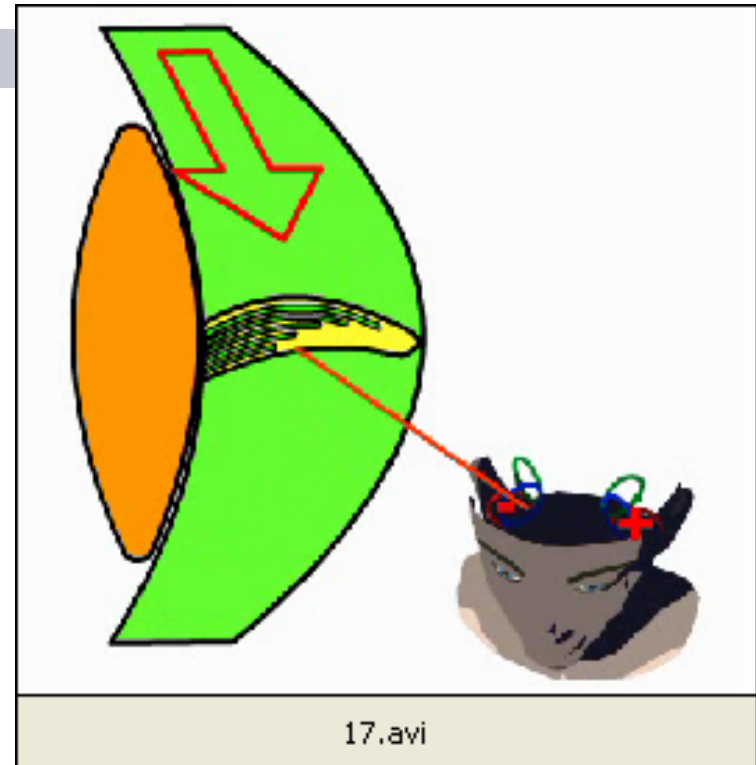


# I canali semicircolari

- Oscillatore smorzato

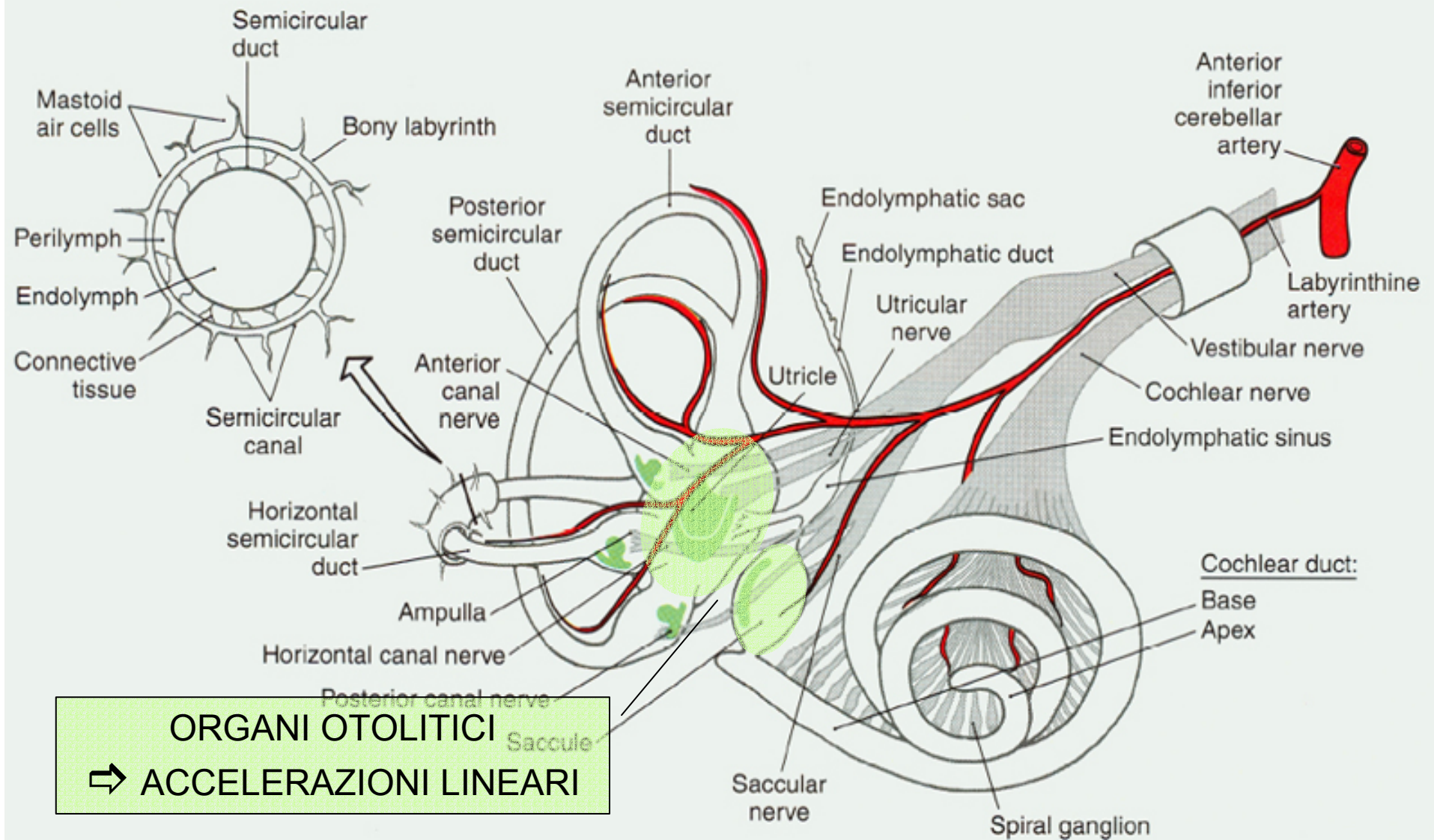
$$\theta(s) = \frac{\alpha s}{(T_1 s + 1)(T_2 s + 1)} \dot{q}(s)$$

*Si comporta come un integratore*

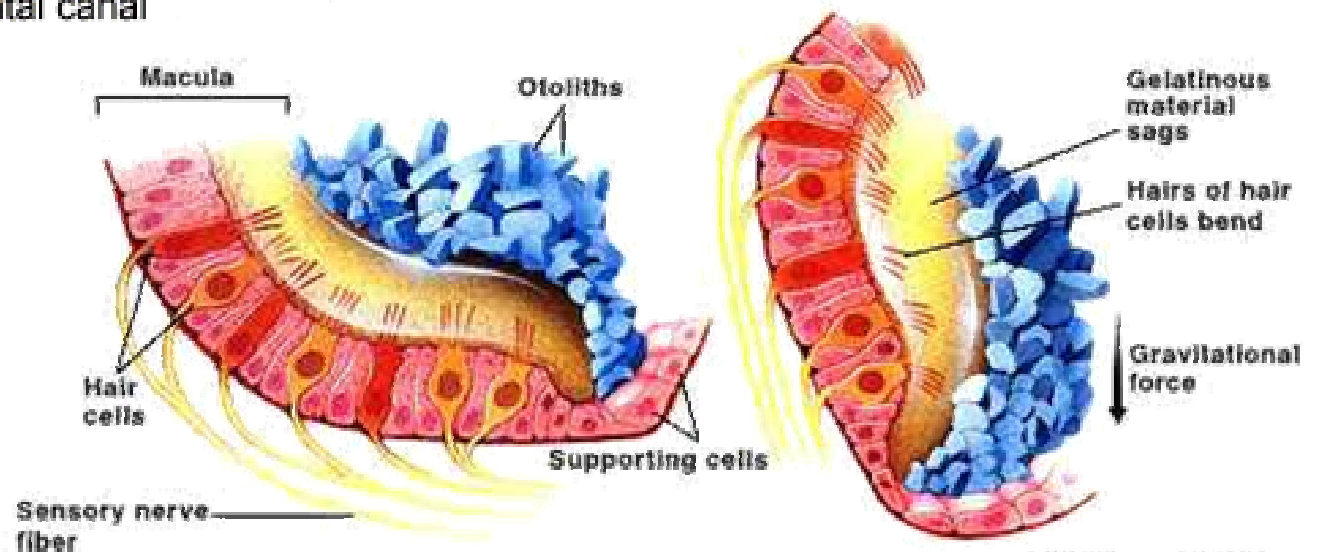
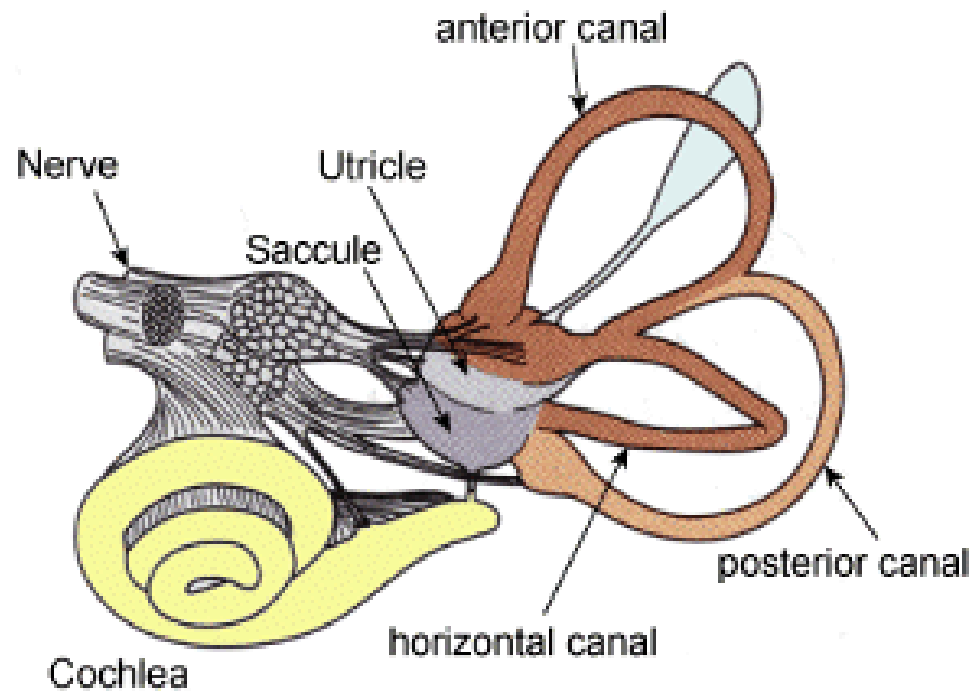


- con  $\theta$  = deflessione della cupula,  $\dot{q}$  = velocità della testa,  $\alpha$  = fattore proporzionale e  $s$  = frequenza
- Nell'Uomo, le costanti di tempo  $T_1$  e  $T_2$  sono approssimativamente 3 ms and 5 s, rispettivamente
- Per movimenti tipici della testa, con frequenze da 0.1 Hz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

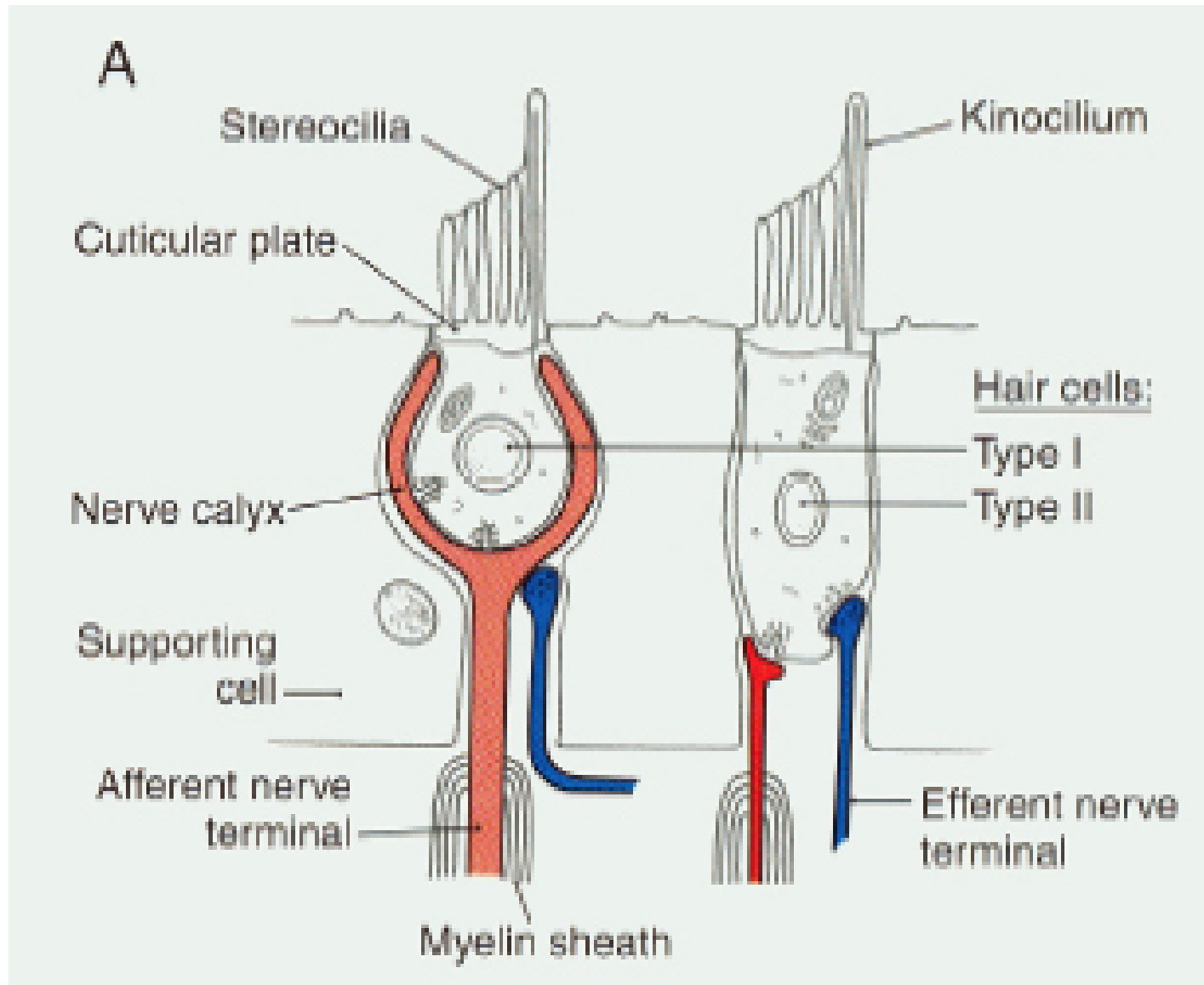
# Gli organi otolitici



# 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.

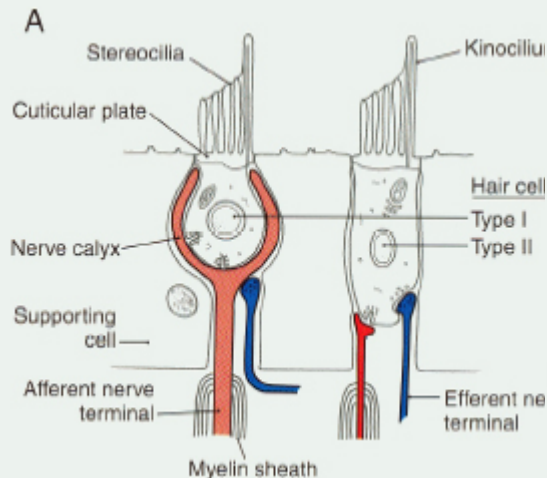
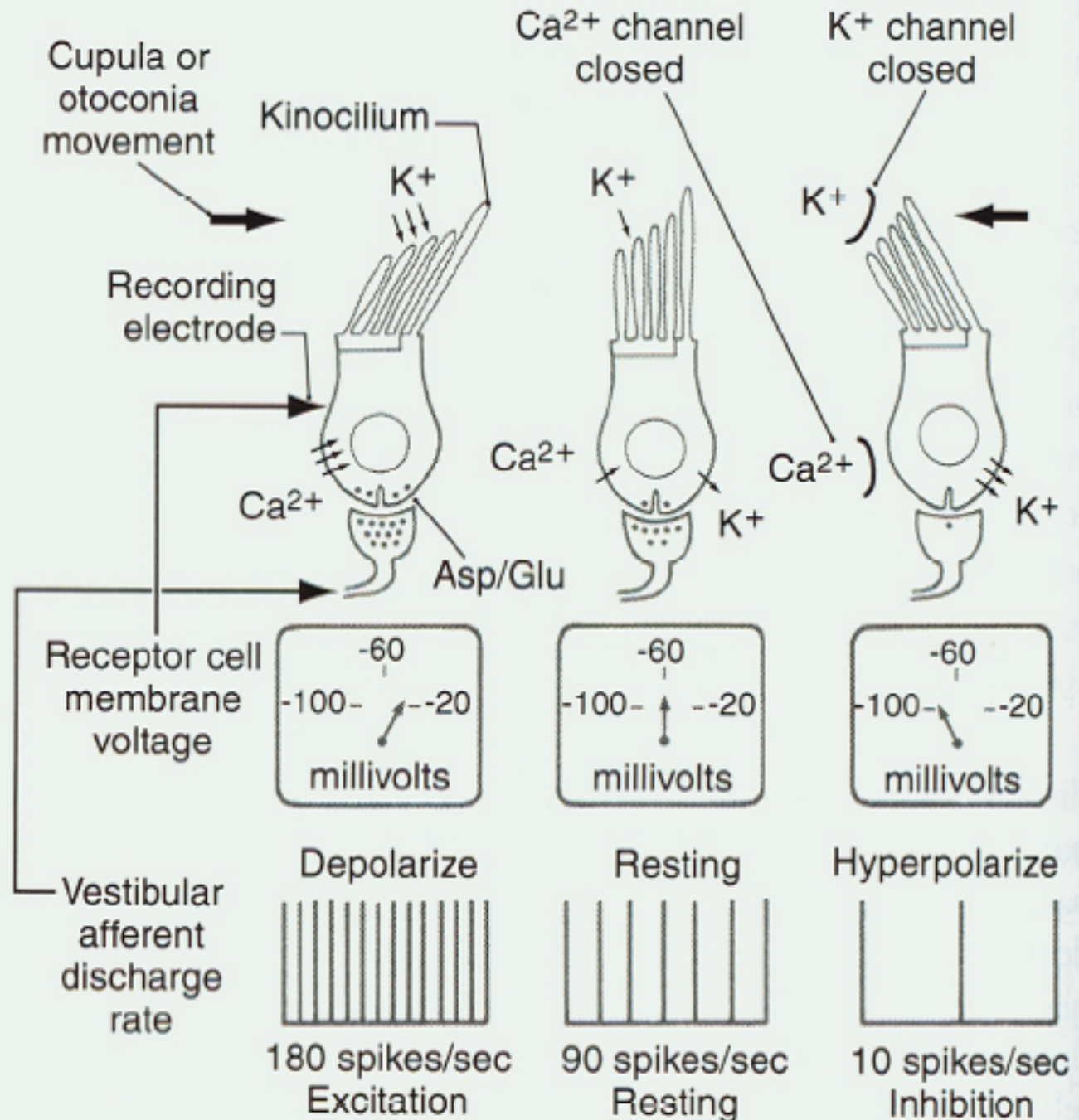


Start Labyrinth Otoliths Canals VOR Dizzy Plasticity End





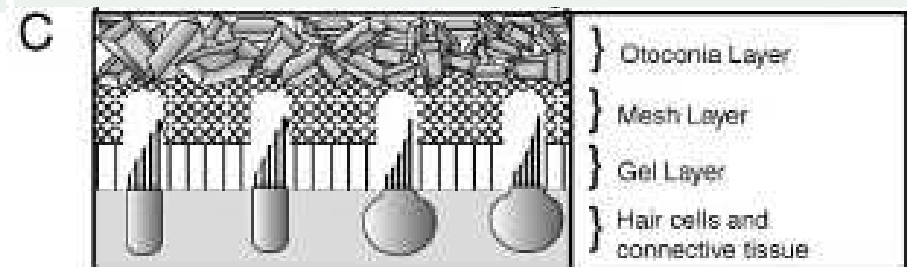
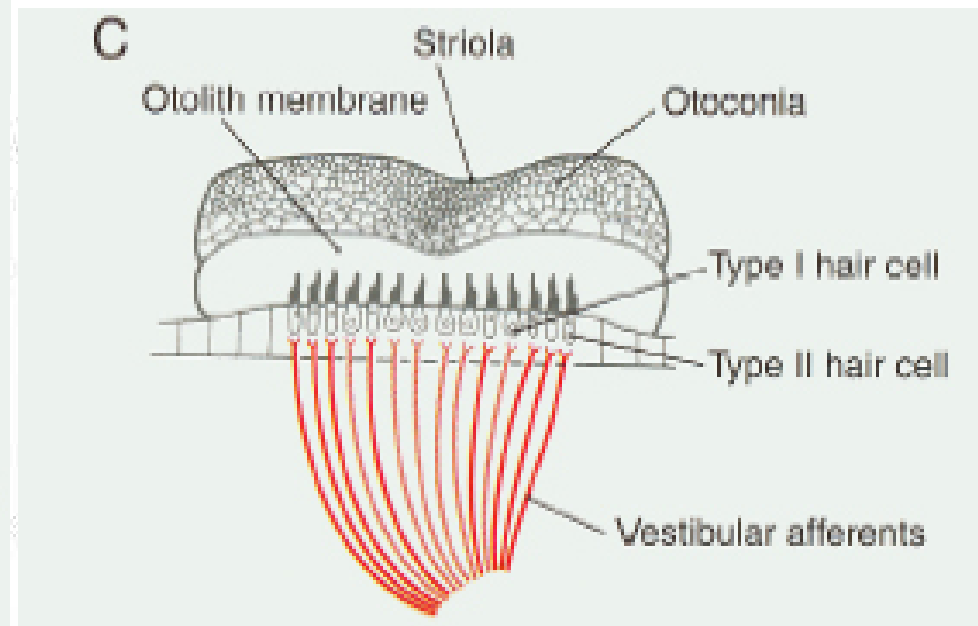
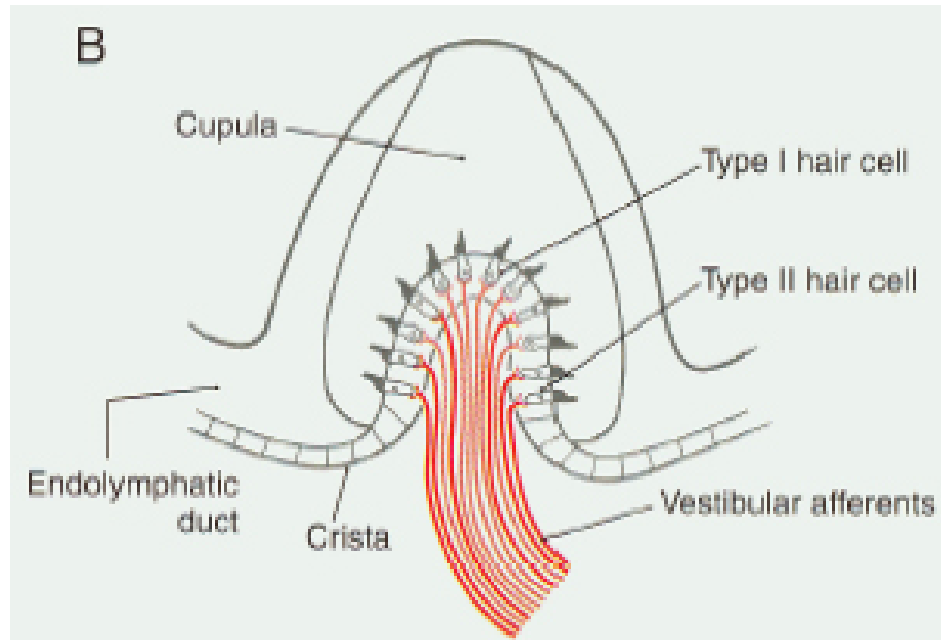
# I recettori vestibolari



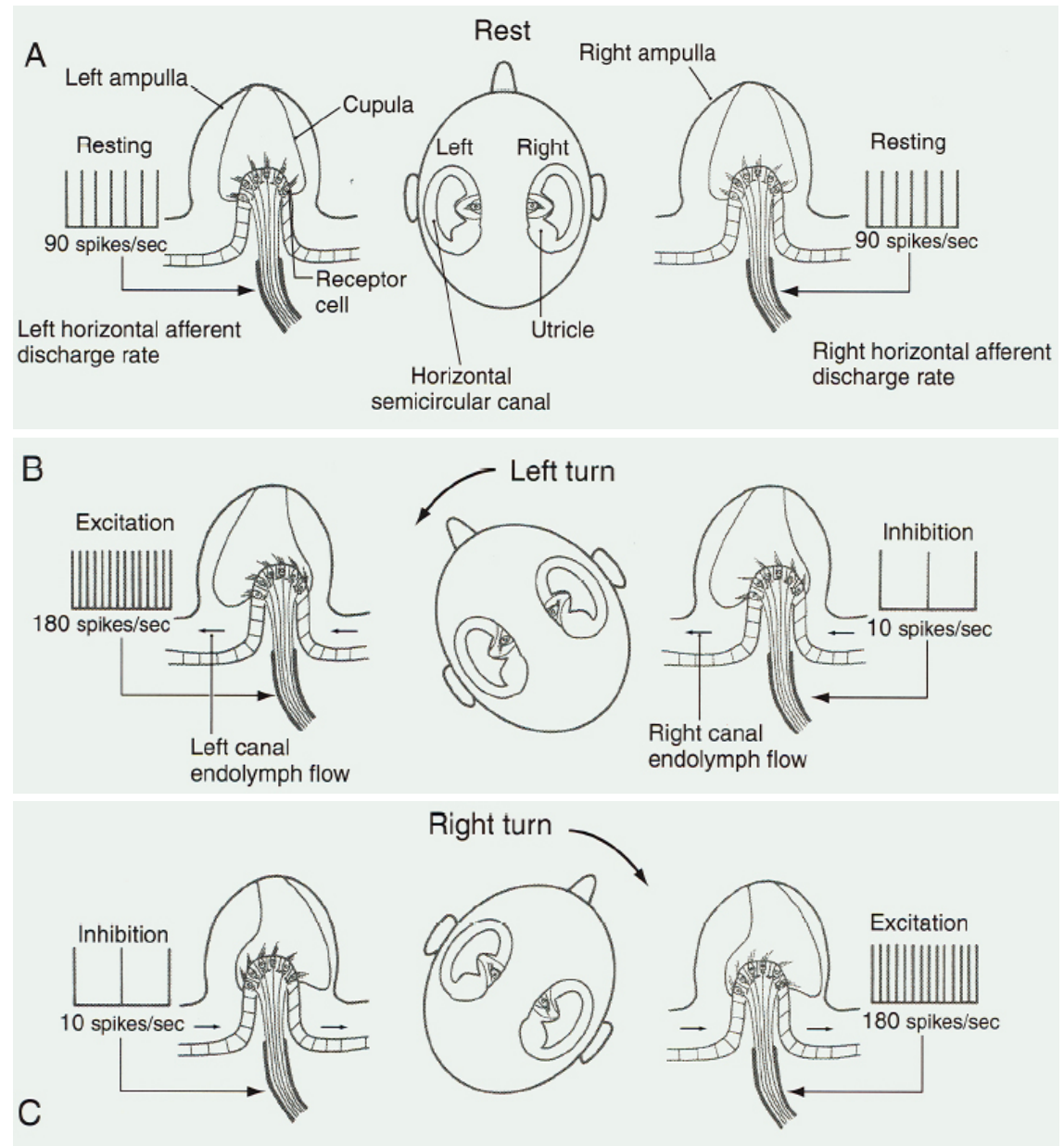
# I recettori vestibolari nei canali semicircolari e negli organi otolitici

## ■ Canali semicircolari

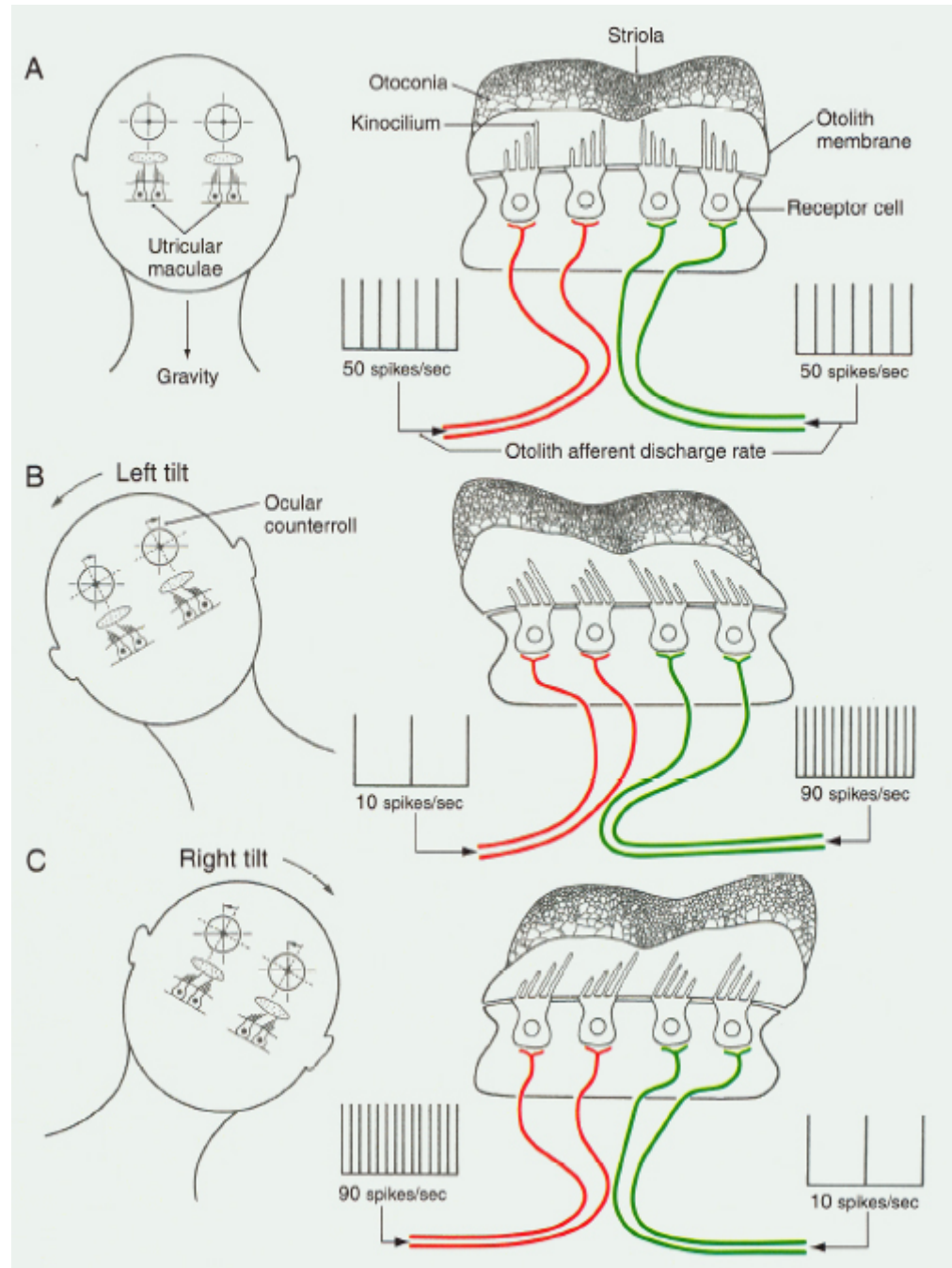
## ■ Organi otolitici



# 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.



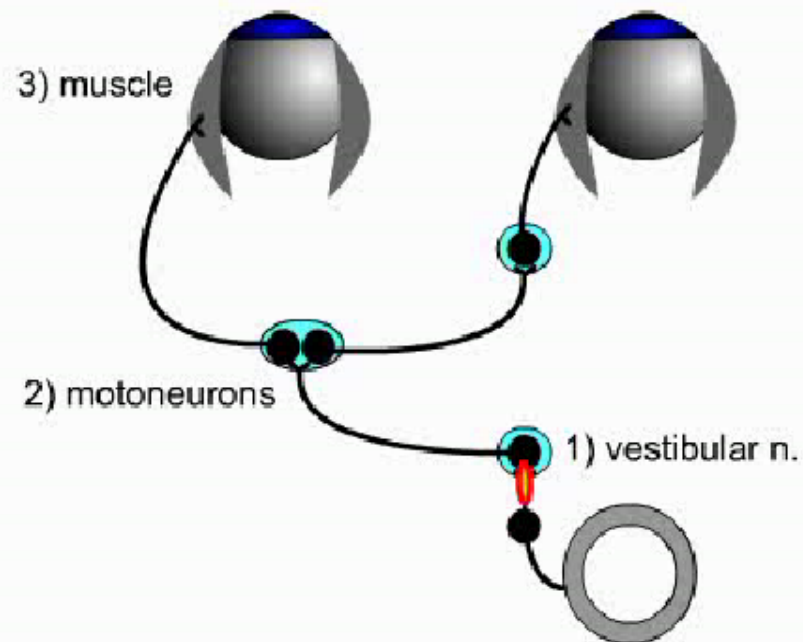
Start Labyrinth Otoliths Canals VOR Dizzy Plasticity End

undici.avi

## II Riflesso Vestibulo-Oculare (VOR)

Explain the neural mechanism for a horizontal VOR.

The direct path is a short reflex with 3 synapses.



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## II Riflesso Vestibulo-Oculare (VOR)

Explain the neural mechanism for a horizontal VOR.

When the head rotates rightward the following occurs.

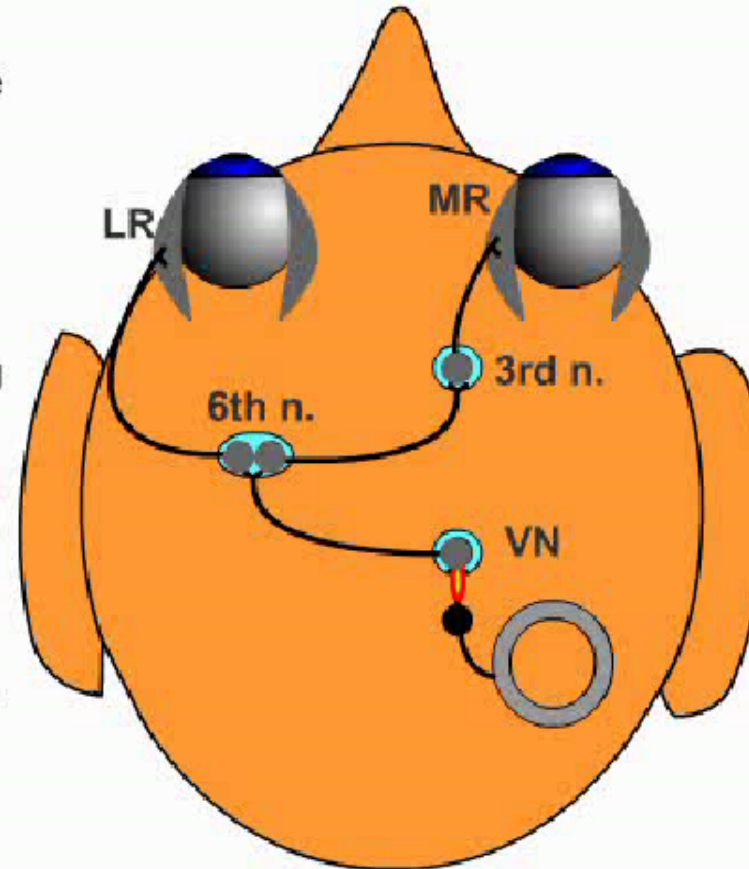
The right horizontal canal hair cells depolarize.

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.



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## 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.

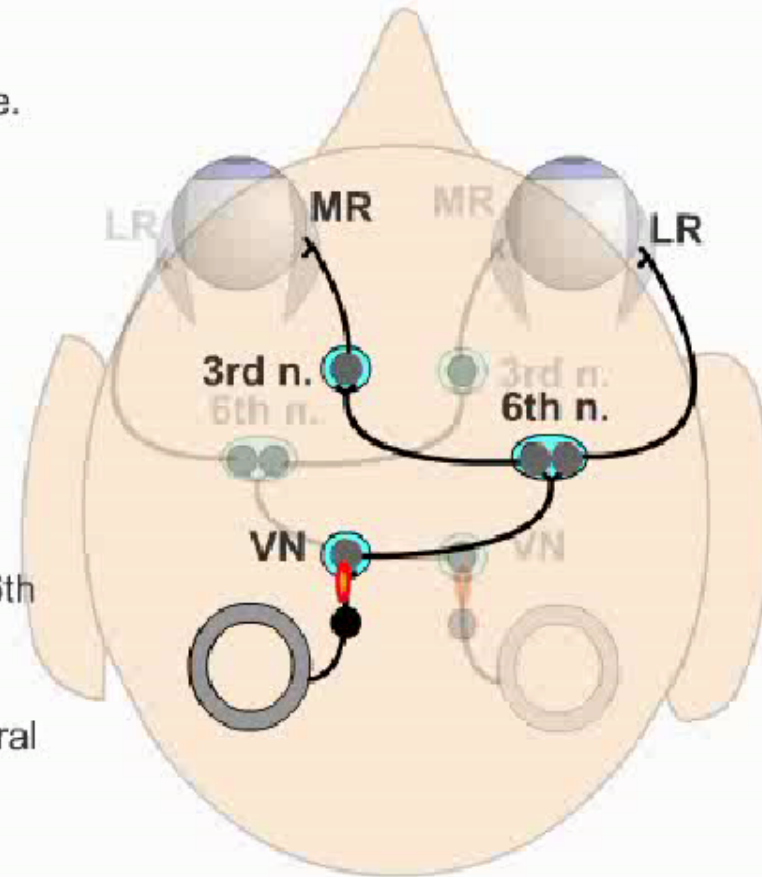
The left horizontal canal hair cells hyperpolarize.

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





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# Quantità cinematiche

## ■ Posizione

□  $x(t); \theta(t)$

## ■ Velocità

□  $v(t); \omega(t)$

## ■ Accelerazione

□  $a(t); \alpha(t)$

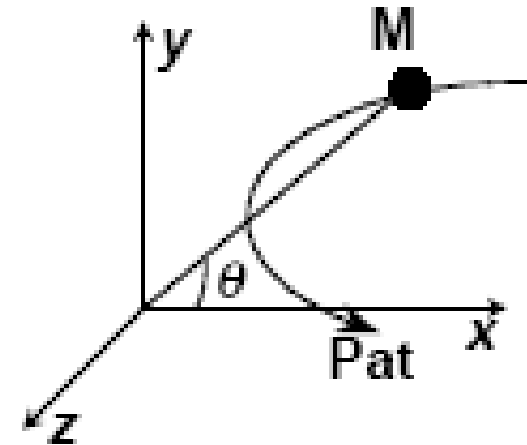
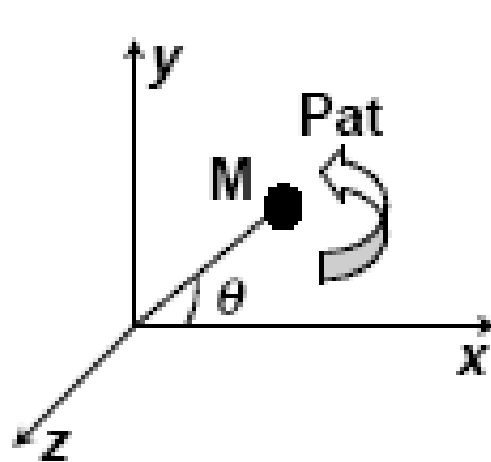
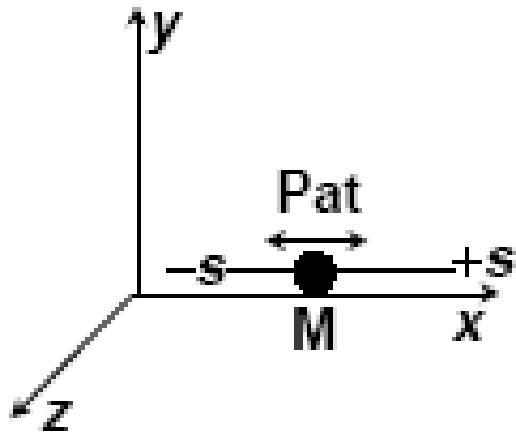
## ■ Jerk

□ ...

The diagram illustrates the relationships between kinematic quantities using differentiation and integration arrows:

- From Position to Velocity:  $\frac{d}{dt}$  (downward arrow)
- From Velocity to Position:  $\int dt$  (upward arrow)
- From Velocity to Acceleration:  $\frac{d}{dt}$  (downward arrow)
- From Acceleration to Velocity:  $\int dt$  (upward arrow)
- From Acceleration to Jerk:  $\frac{d}{dt}$  (downward arrow)
- From Jerk to Acceleration:  $\int dt$  (upward arrow)

# 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:

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

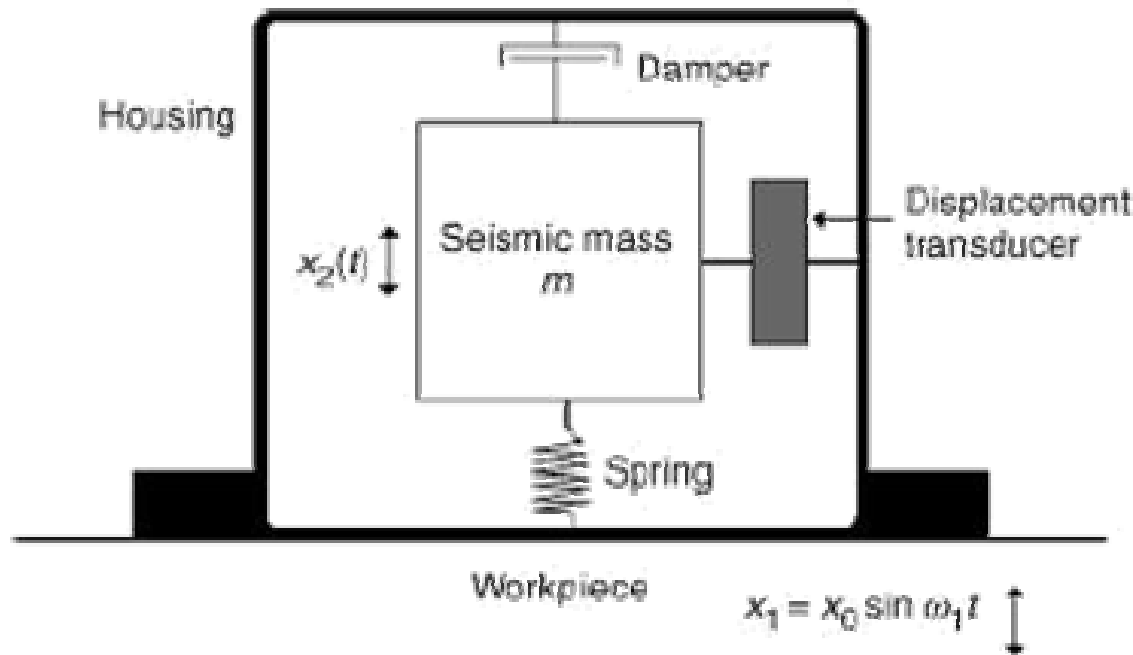


# Misura dell'accelerazione

- 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



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

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

$$z = x_2 - x_1$$

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

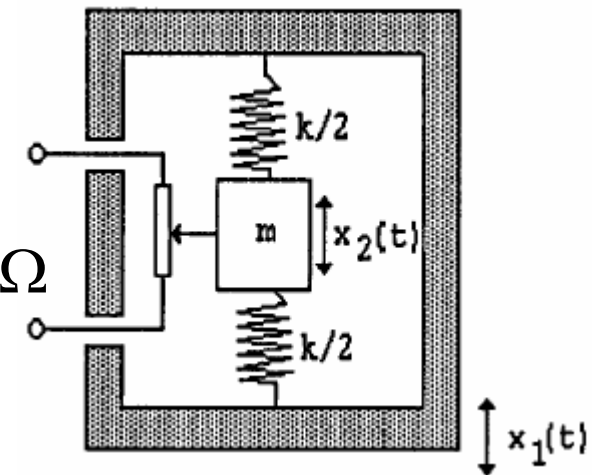


# Principali tecnologie

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

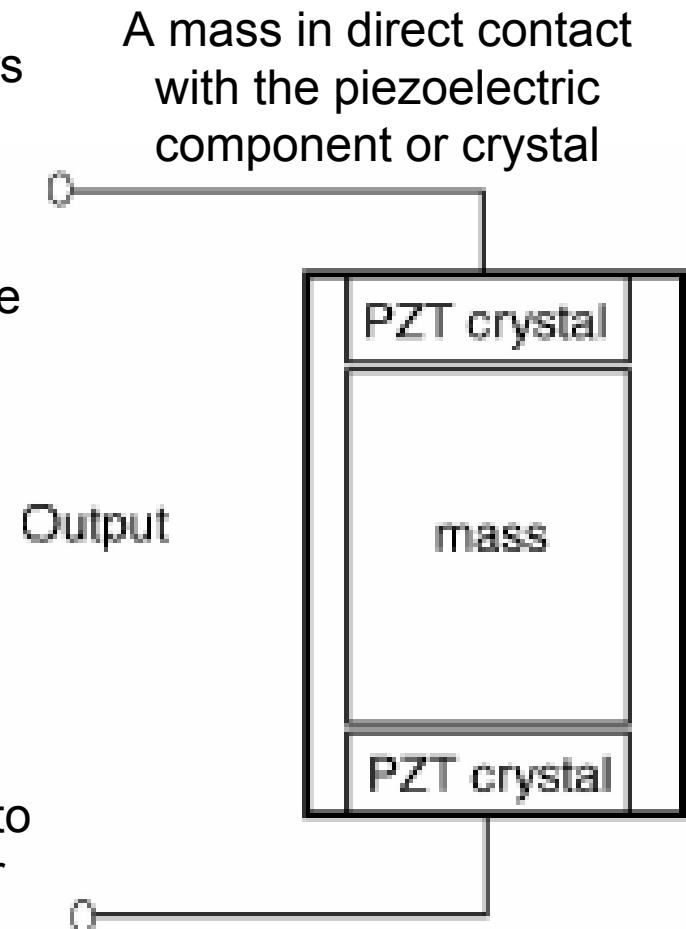
# Accelerometri potenziometrici

- 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  $\zeta$ : 0.5- 0.8
- Resistenza del potenziometro: 1000–10000  $\Omega$ 
  - Risoluzione corrispondente: 0.45–0.25% fs.
- Sensibilità cross- assiale:  $< \pm 1\%$ .
- Accuratezza:  $\pm 1\%$  fs a temperatura ambiente.
- Dimensioni: 50mm<sup>3</sup> (<0.1 gr.)



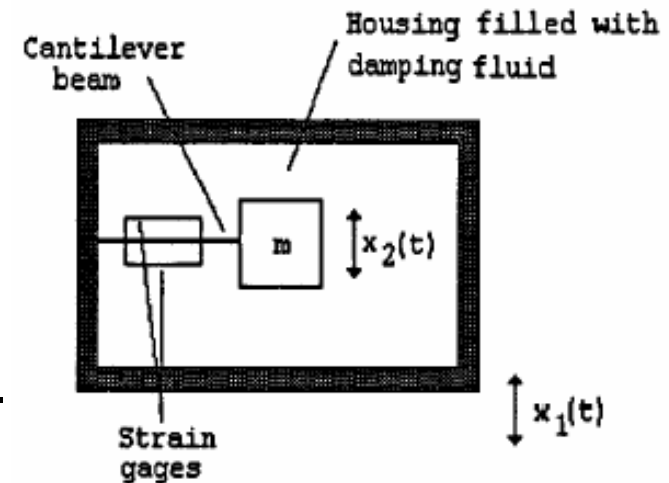
# Accelerometri piezoelettrici

- 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%.



# Accelerometri a strain gauge

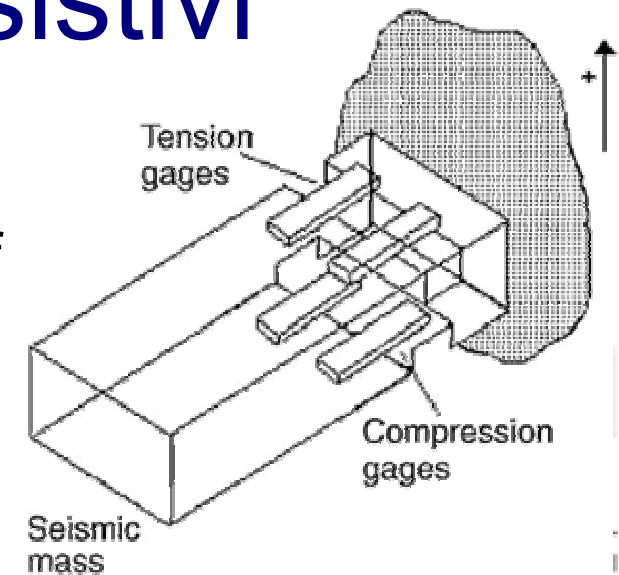
- Electric resistance strain gauges are also used for displacement sensing of the seismic mass
  - the seismic mass is mounted on a cantilever beam rather than on springs.



- 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

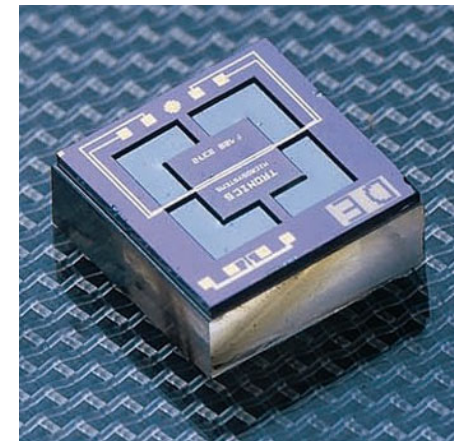
- Piezoresistive accelerometers are essentially semiconductor strain gauges with large gauge factors. The sensitivity of a piezoresistive sensor comes from the elastic response of its structure and resistivity of the material.
- Piezoresistive accelerometers are useful for acquiring vibration information 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







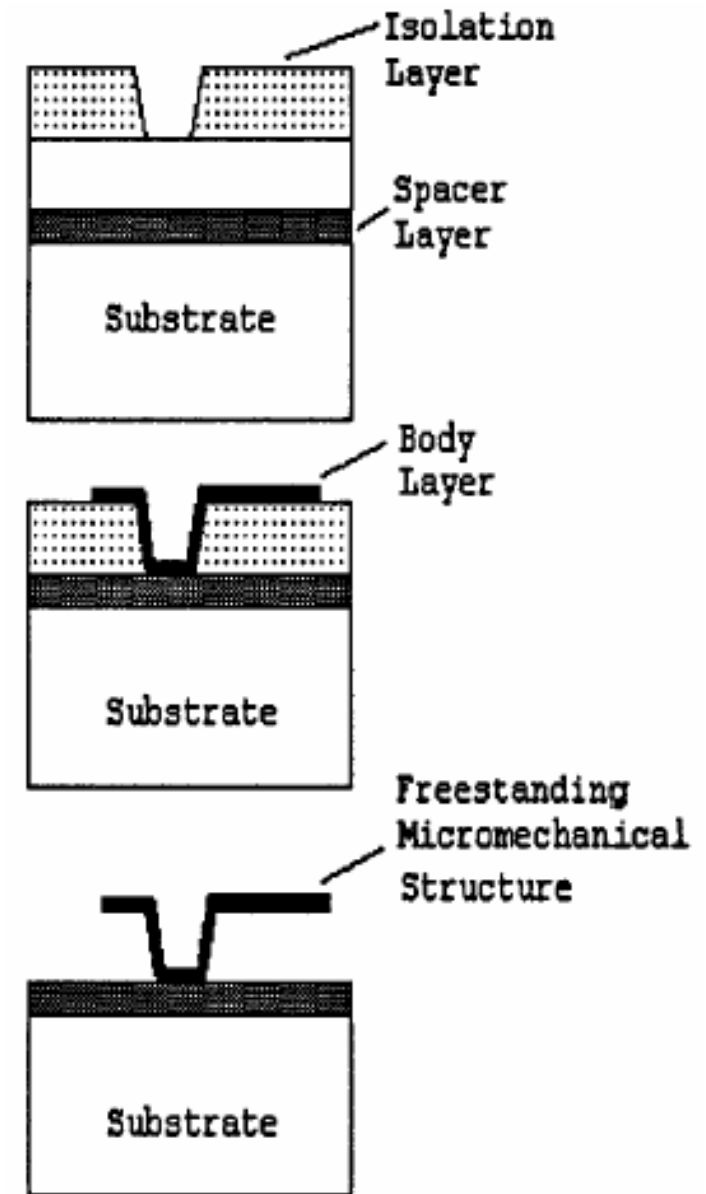
# Inductive transducers

## ■ 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

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

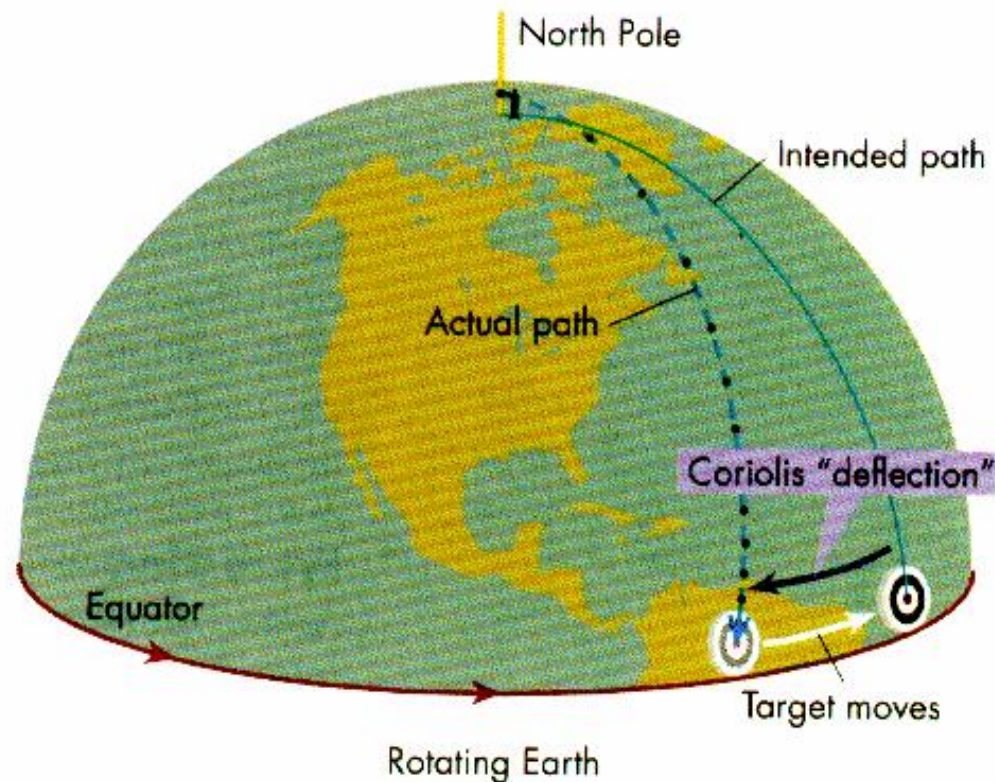


# Misura della velocità angolare: giroscopi

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 sull'accelerazione di Coriolis

## Vibrating mass gyroscopes

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

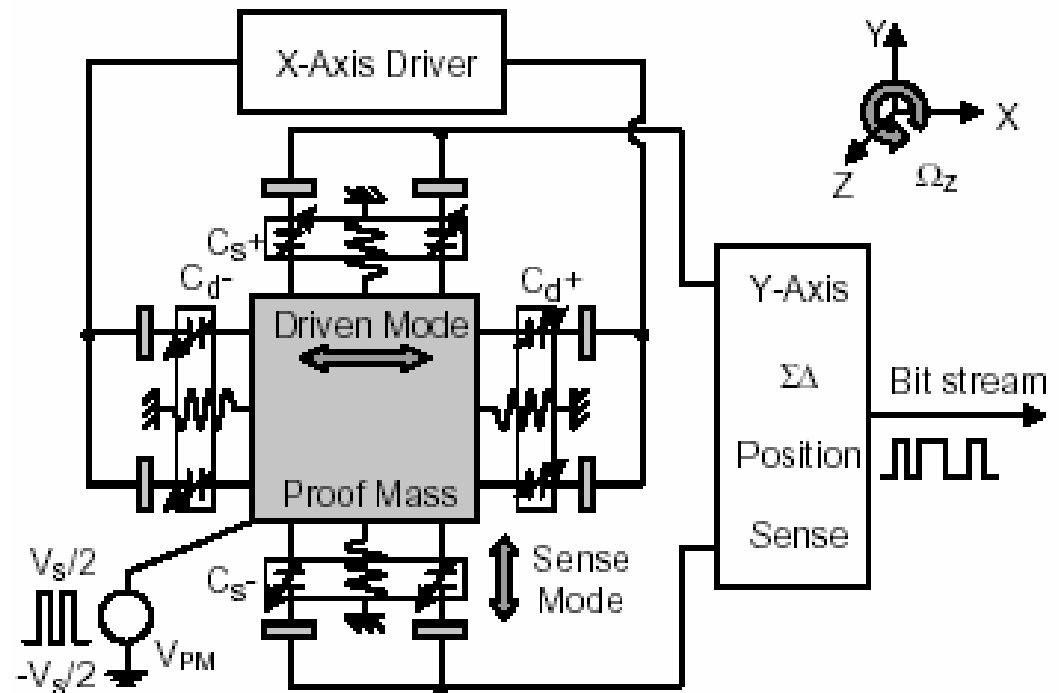
If the sensor is rotated about an axis orthogonal to this velocity, a Coriolis acceleration is induced

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

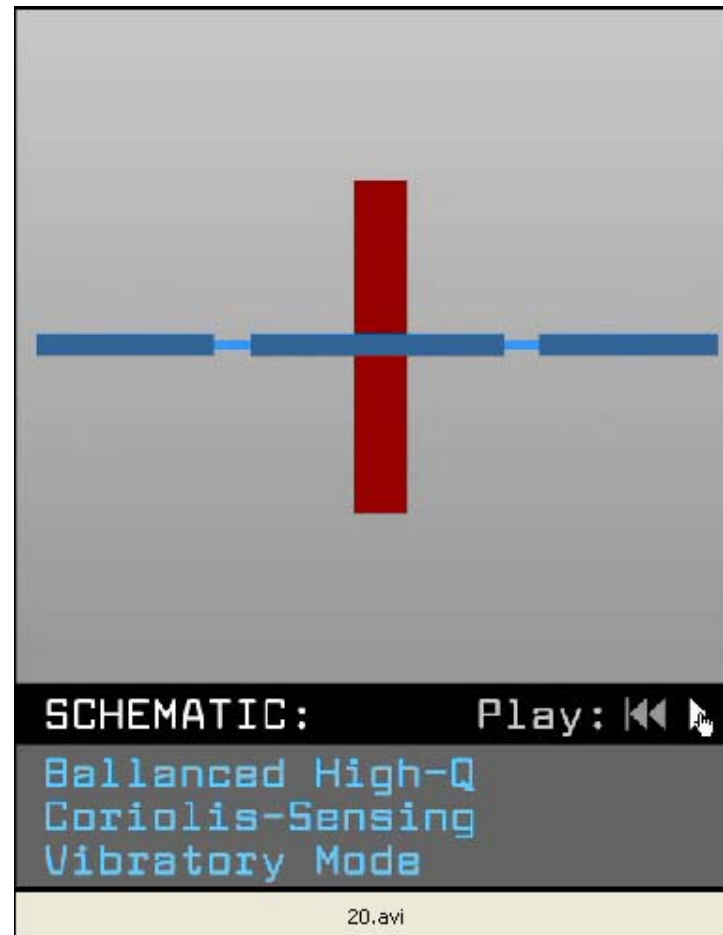
by:  $\mathbf{F}_C = -2m(\boldsymbol{\omega} \times \mathbf{v})$





# 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





# 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

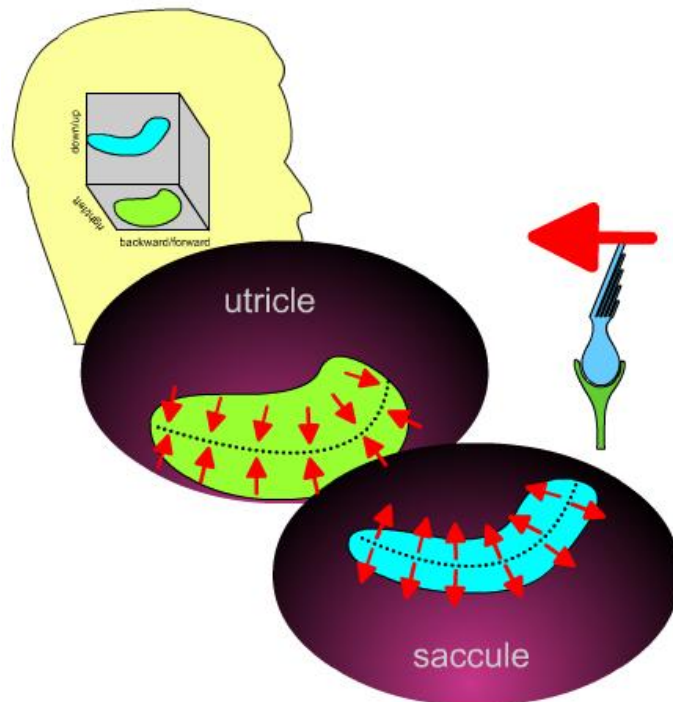
A biologically inspired artificial vestibular system has to be able to detect:

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



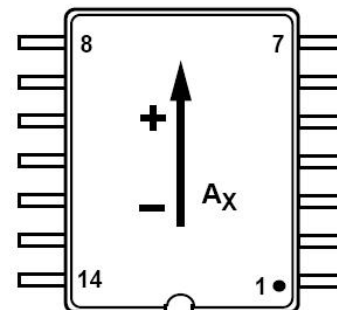
- |   |
|---|
| <ul style="list-style-type: none"><li>• Pitch, Roll and Yaw angular velocity</li><li>• Direction and magnitude of gravity</li><li>• X, Y and Z-direction transient acceleration</li></ul> |
|---|

# 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

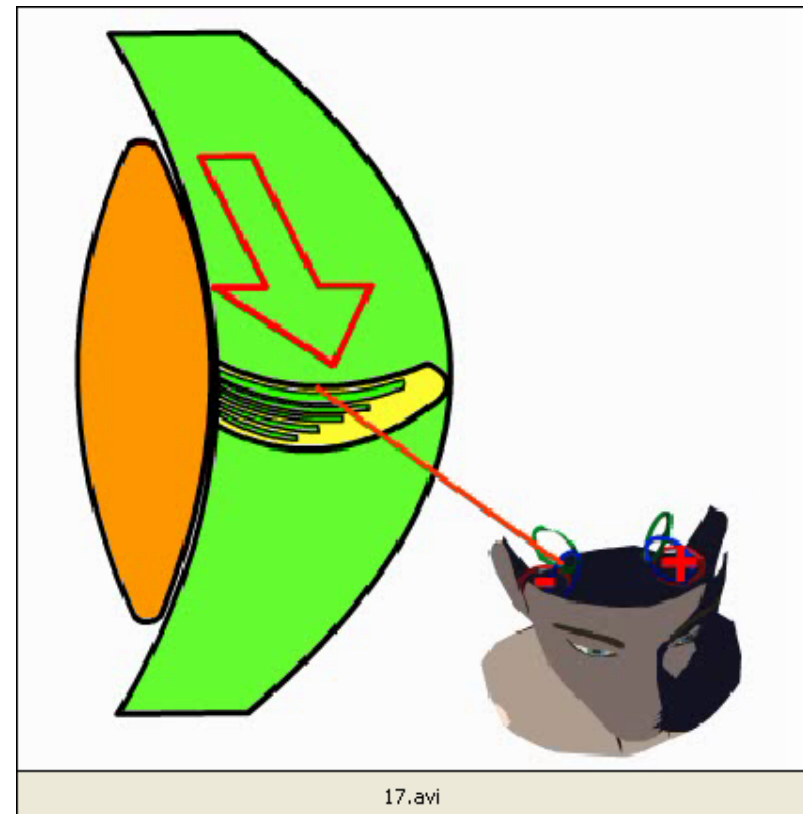


# Artificial Vestibular System



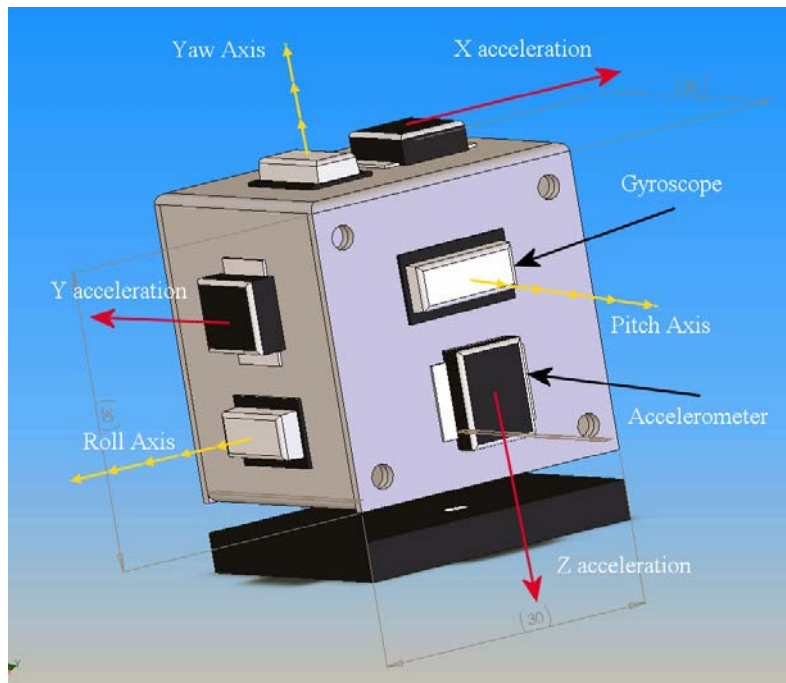
Angular velocity  
detector: Gyroscope

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.



# Artificial Vestibular System I

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



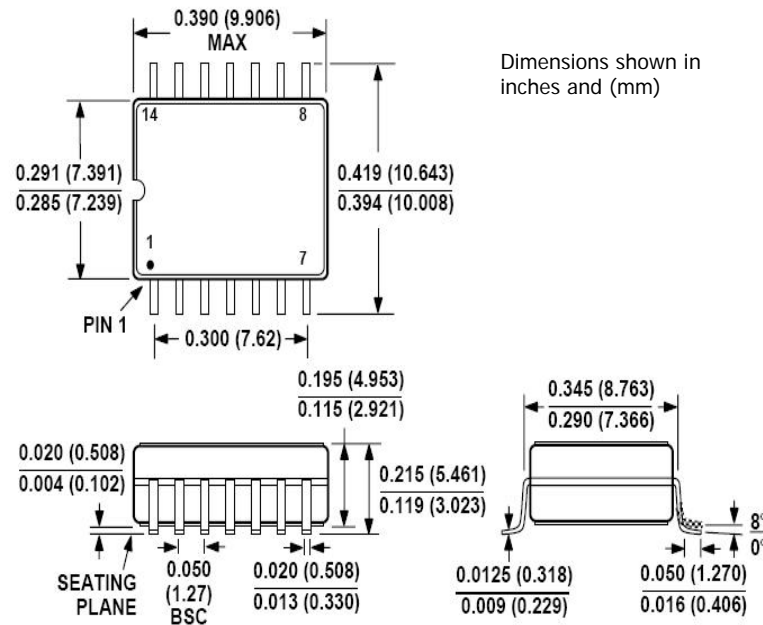
3 mono-axial Piezoelectric  
Vibrating Gyroscopes

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 $\pm 40$ , Max $\pm 50$	$g$
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.

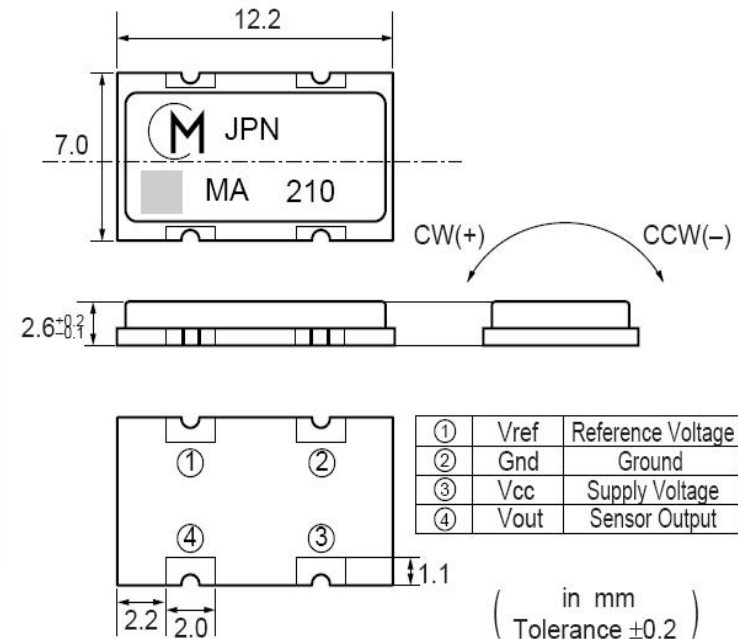


# Gyroscope Features

## Piezoelectric Vibrating Gyroscopes by Murata

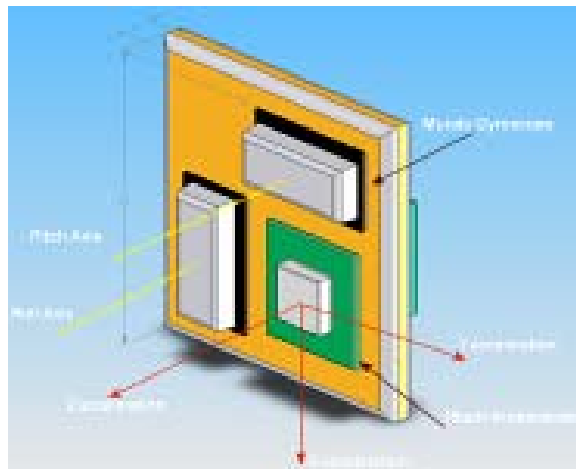
This product is an angular velocity sensor that uses the phenomenon of Coriolis force and achieve an ultra-small size of about 0.2cc. Its small and lightweight shape increase flexibility of installment and let the apparatus to be downsized.

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

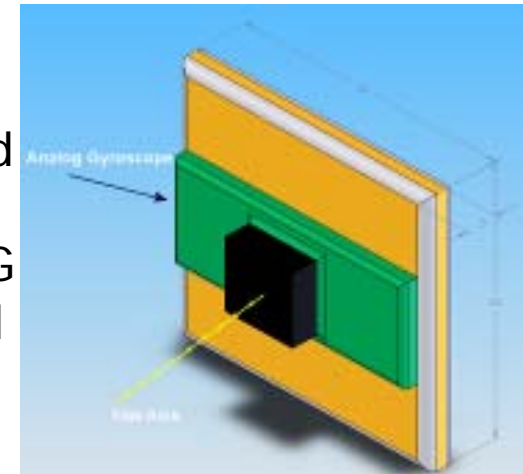


Supply Voltage (Vdc)	Maximum Angular Velocity (deg./sec.)	Output (at Angular Velocity=0) (Vdc)	Scale Factor (mV/deg./sec.)	Response (Hz)	Weight (g)
2.7-5.25	+/-300	1.35	0.67	50 max.	0.4

# 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

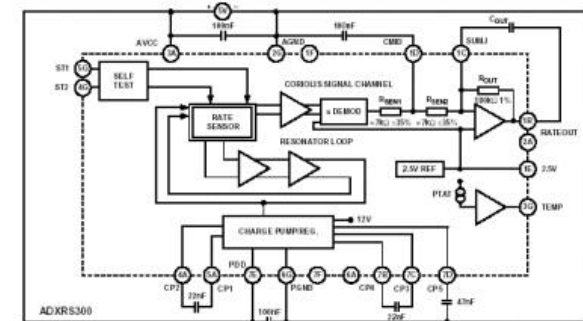
	Unit	Standard products	Newly developed sensor	Remarks
Package size	mm	$4.8 \times 4.8$	$4.8 \times 4.8$	
Package thickness	mm	1.5	1.3	
Acceleration detection range	G	$\pm 3$	$\pm 2$	
Power-source voltage	V	2.2 to 3.6	2.2 to 3.6	
Current drain	mA	0.6	0.4	Power source voltage 3V
Detection sensitivity	mV/G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

## Analog Device Yaw rate Gyroscope

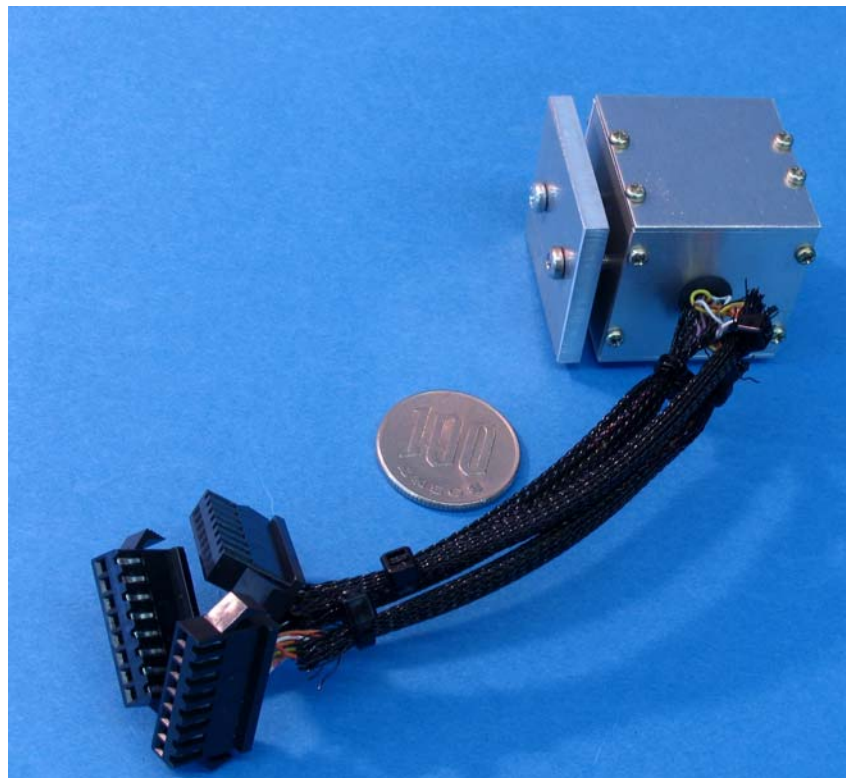
- Complete rate gyroscope on a single chip
- Z-axis (yaw rate) response
- High vibration rejection over wide frequency
- 2000 g powered shock operation
- Self-test on digital command
- Temperature sensor output
- Precision voltage reference output
- Absolute rate output for precision applications
- 5 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



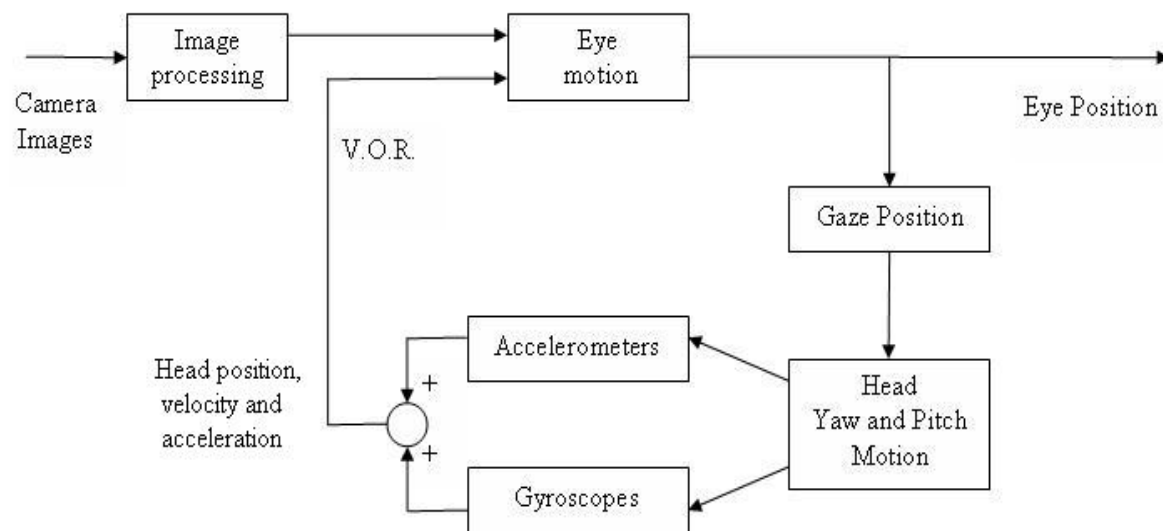
Data coming from the six devices need to be further processed and integrated in order to calculate orientation and position of the head during motion

- 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

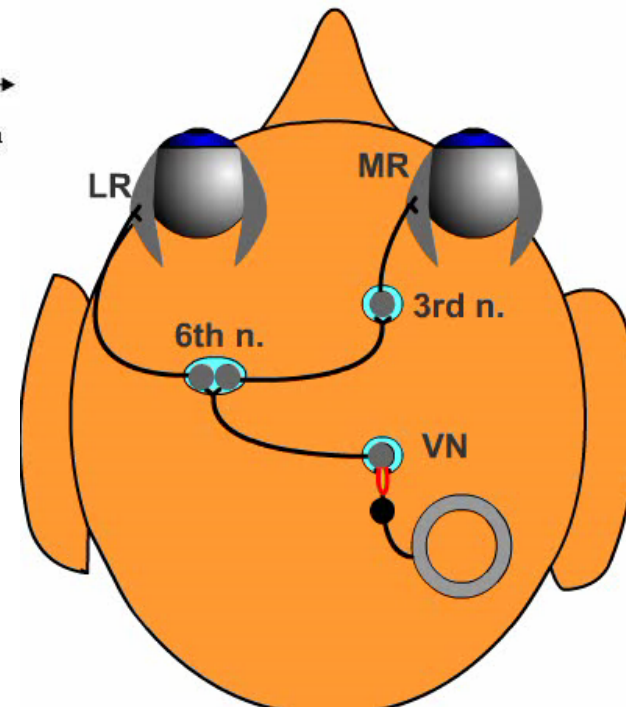
An accurate estimation of accelerations in 3D-space supposes fusing information of the accelerometers and angular velocity sensors

# Outline of the artificial vestibulo-ocular reflexes

## Artificial Vestibulo-ocular Reflex

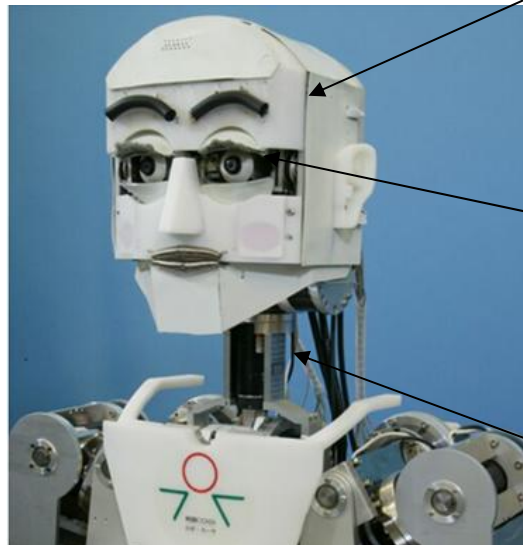


## Human Vestibulo-ocular Reflex



# Experimental tests in detecting robotic head motion

## WE-4RII



Artificial  
vestibular  
system

3 dof for eye  
movements

4 dof for neck  
movements

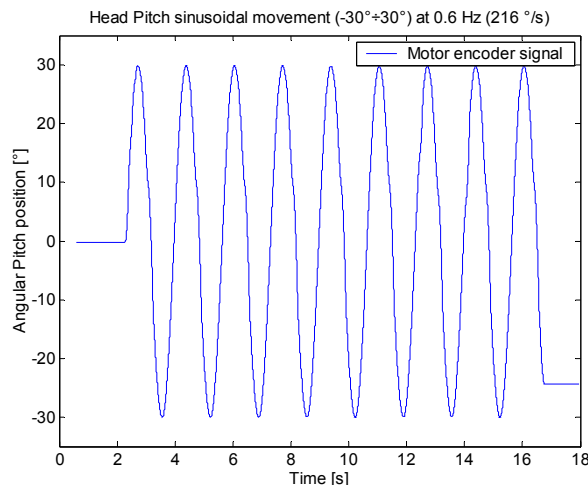
- Impose movements to head (neck):
  - ☐ Upper pitch
  - ☐ Roll
  - ☐ Yaw
- Record the encoder signal
- Record the vestibular system signal
- Compare the two signals



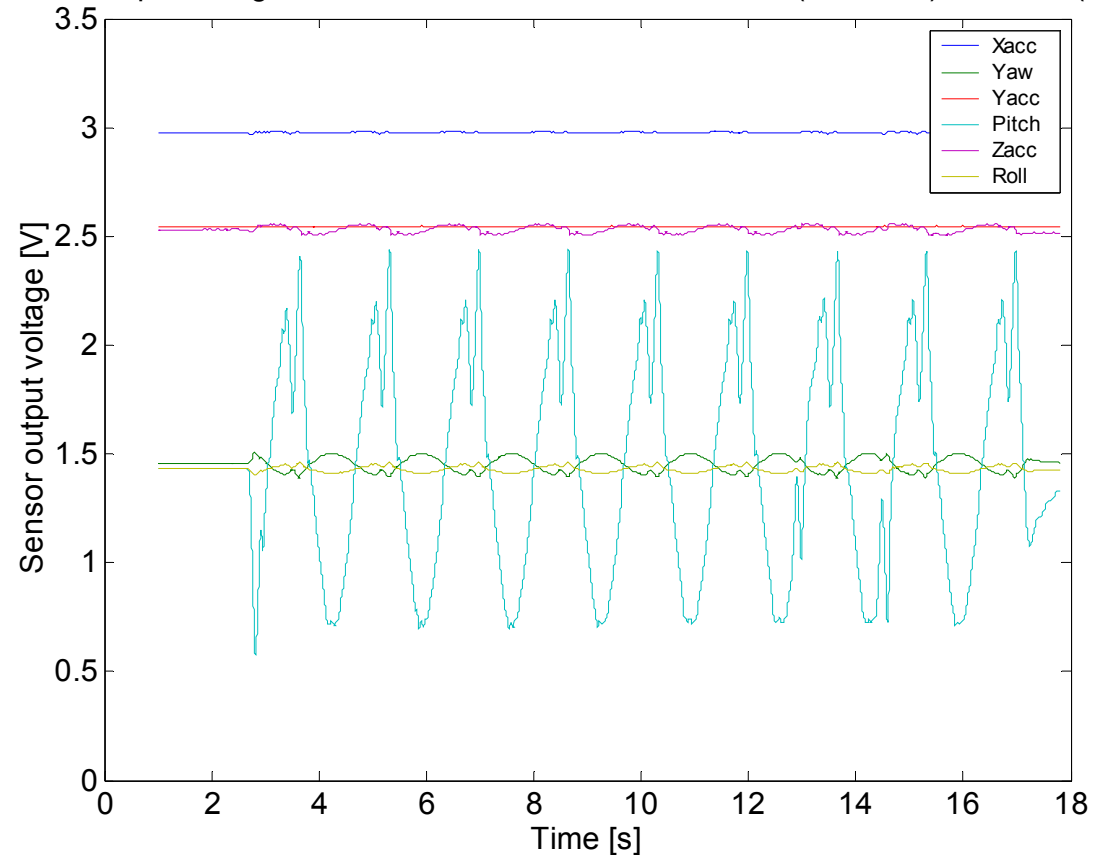
# Experimental results in the detection of the WE-4RII robotic head motion

## 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)

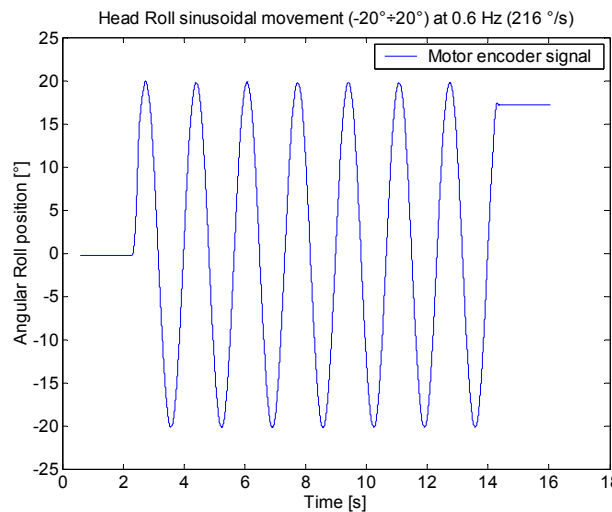




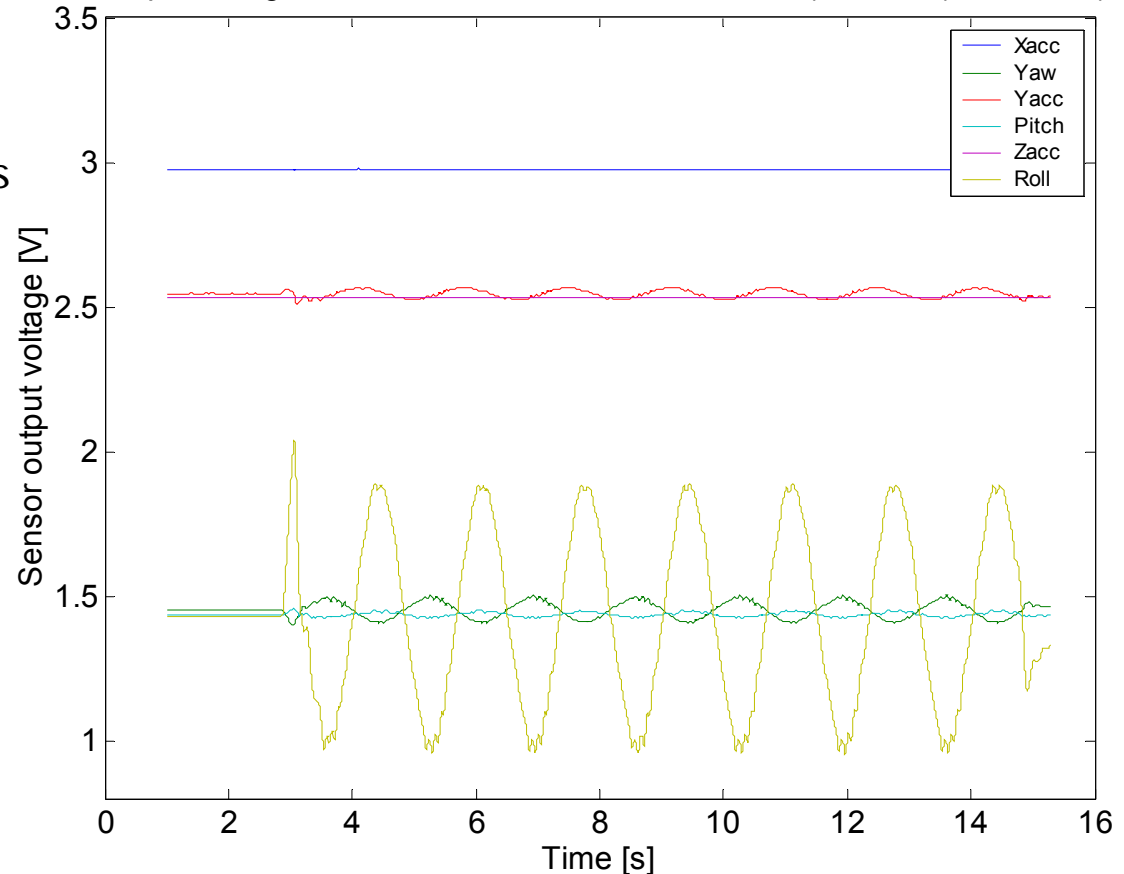
# Experimental results in the detection of the WE-4RII robotic head motion

## 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)

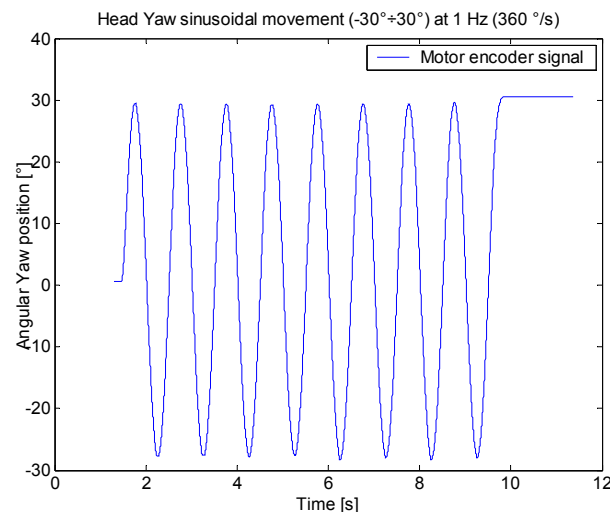


# Experimental results in the detection of the WE-4RII robotic head motion

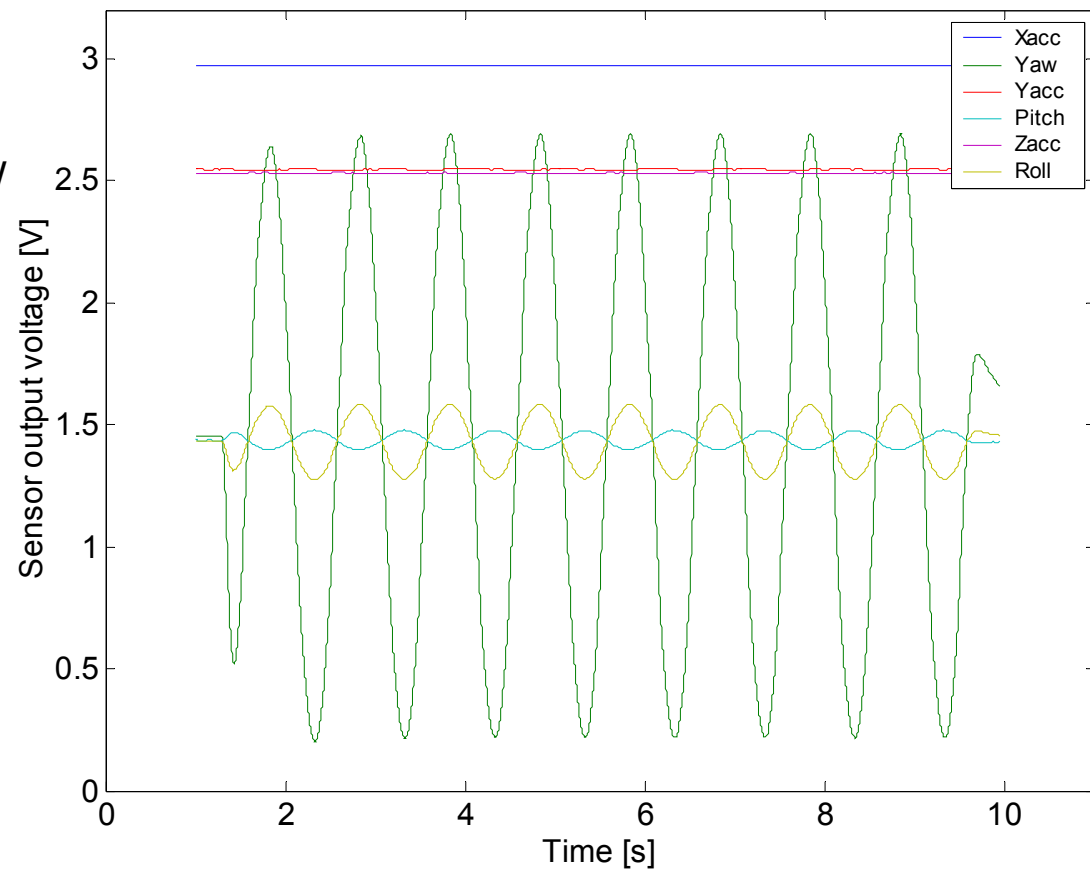
## Yaw

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

All accelerometers silent

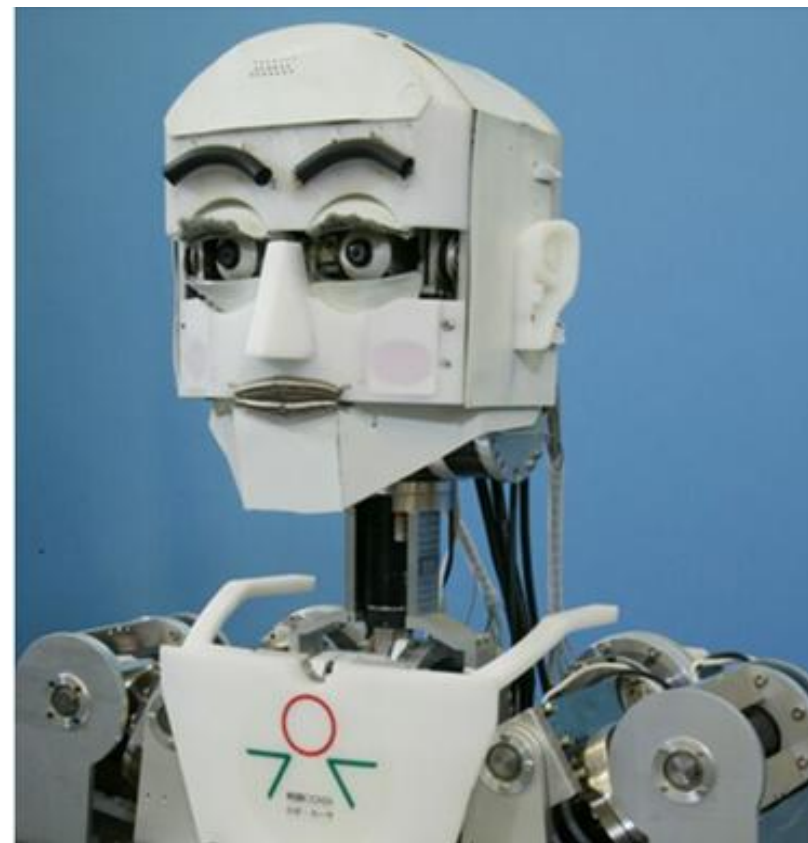
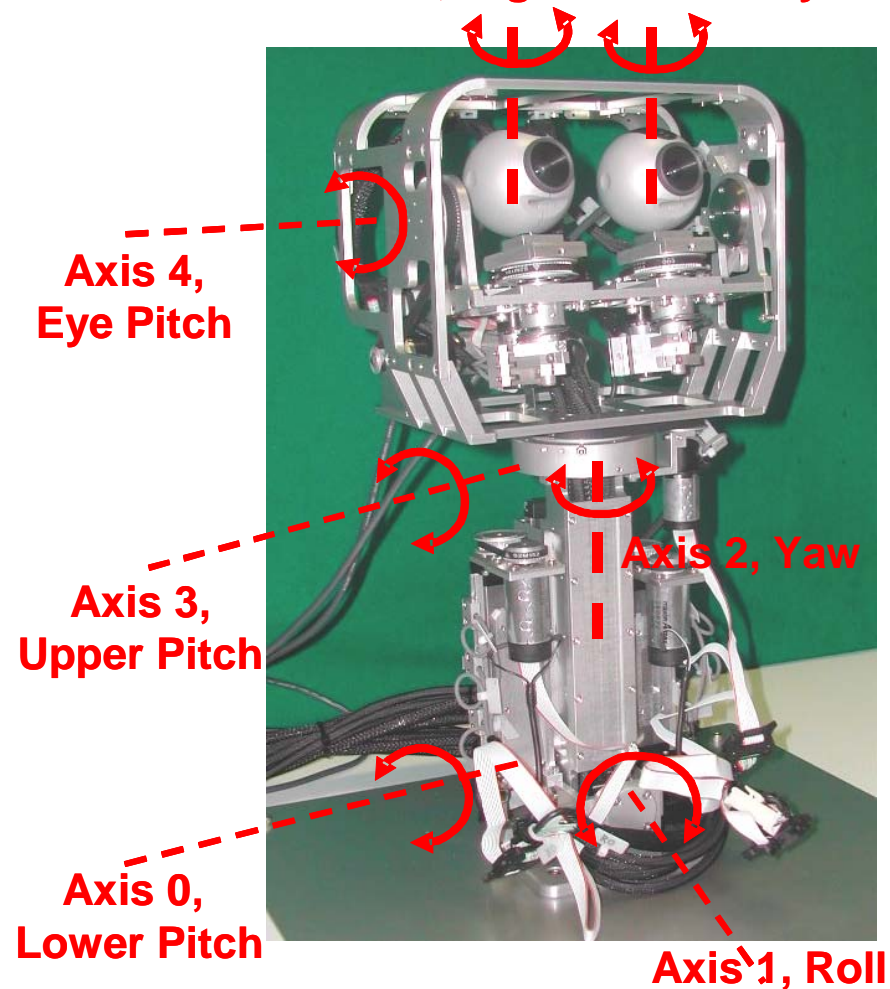


Sensor output voltage for Head Yaw sinusoidal movement ( $-30^\circ \div 30^\circ$ ) at 1 Hz ( $360^\circ/\text{s}$ )

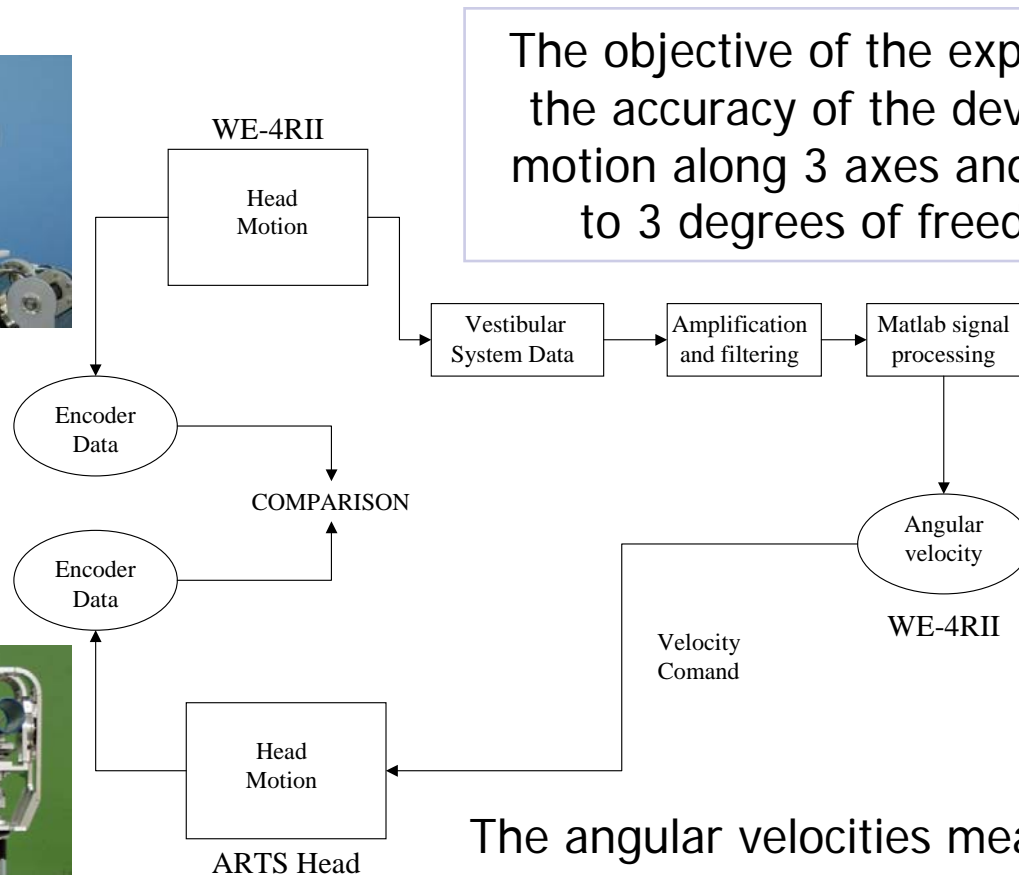


# Experimental validation with two Robotic Heads

Axes 5 and 6, Right and Left Eye Pitch



# Validation Experiments

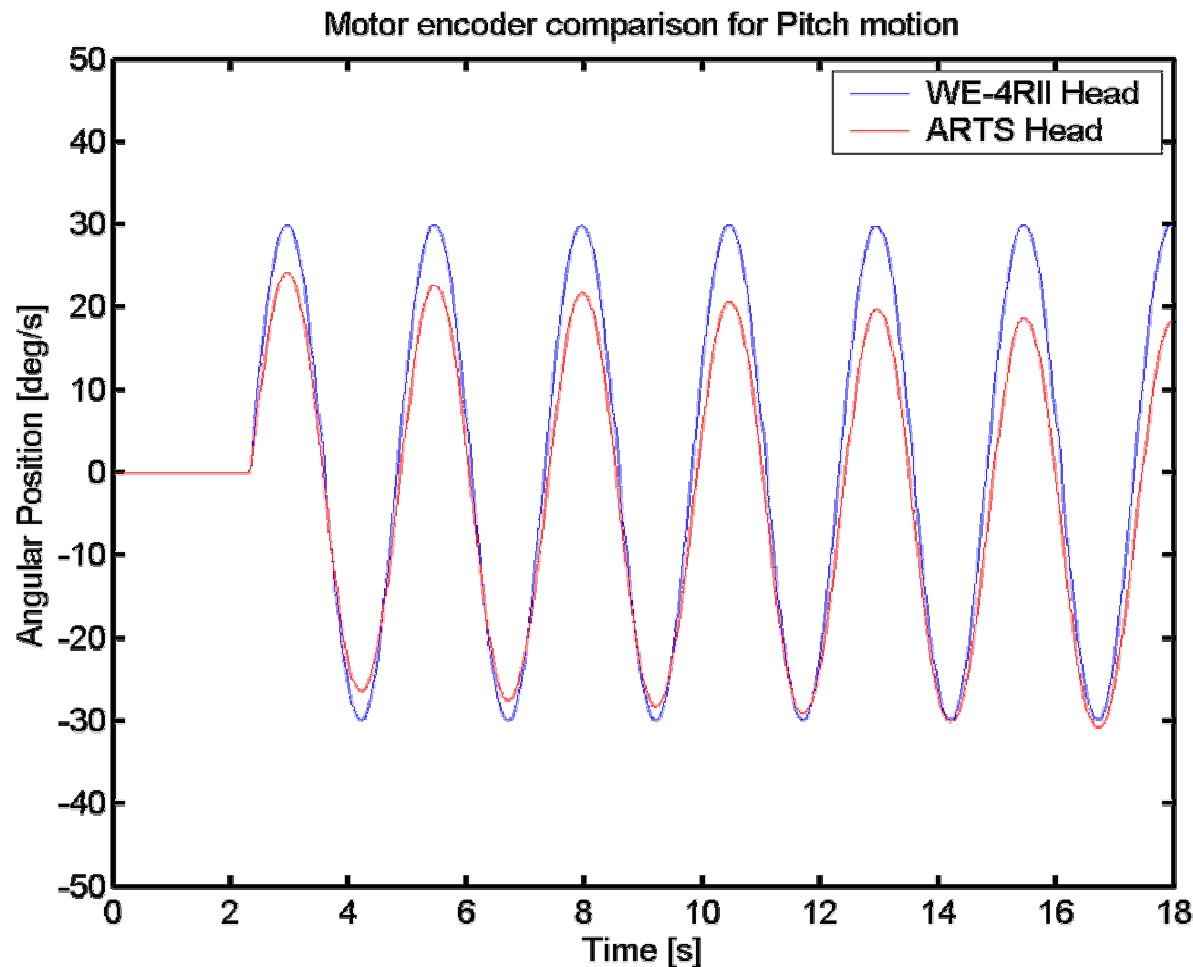


The objective of the experiments is to investigate the accuracy of the developed system to detect motion along 3 axes and to transmit such motion to 3 degrees of freedom of a robotic head.

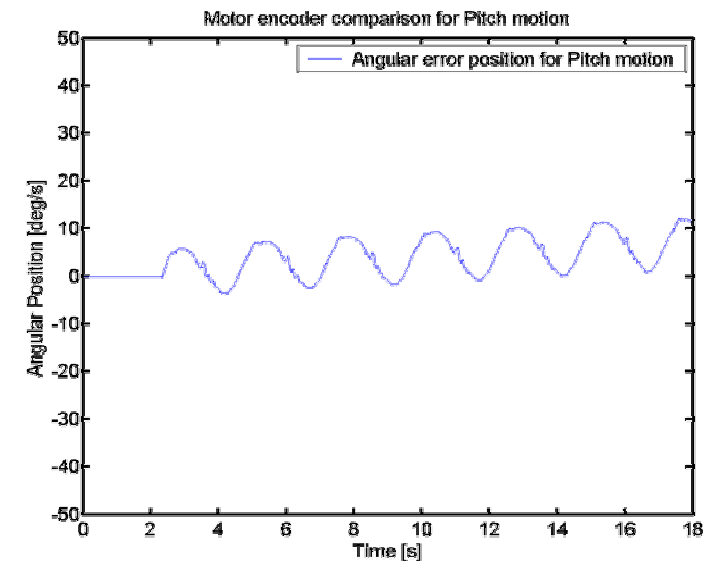
The artificial vestibular system was integrated on the WE-4RII robotic platform and the measured sensory data were used as an external command for the ARTS robotic platform.

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.

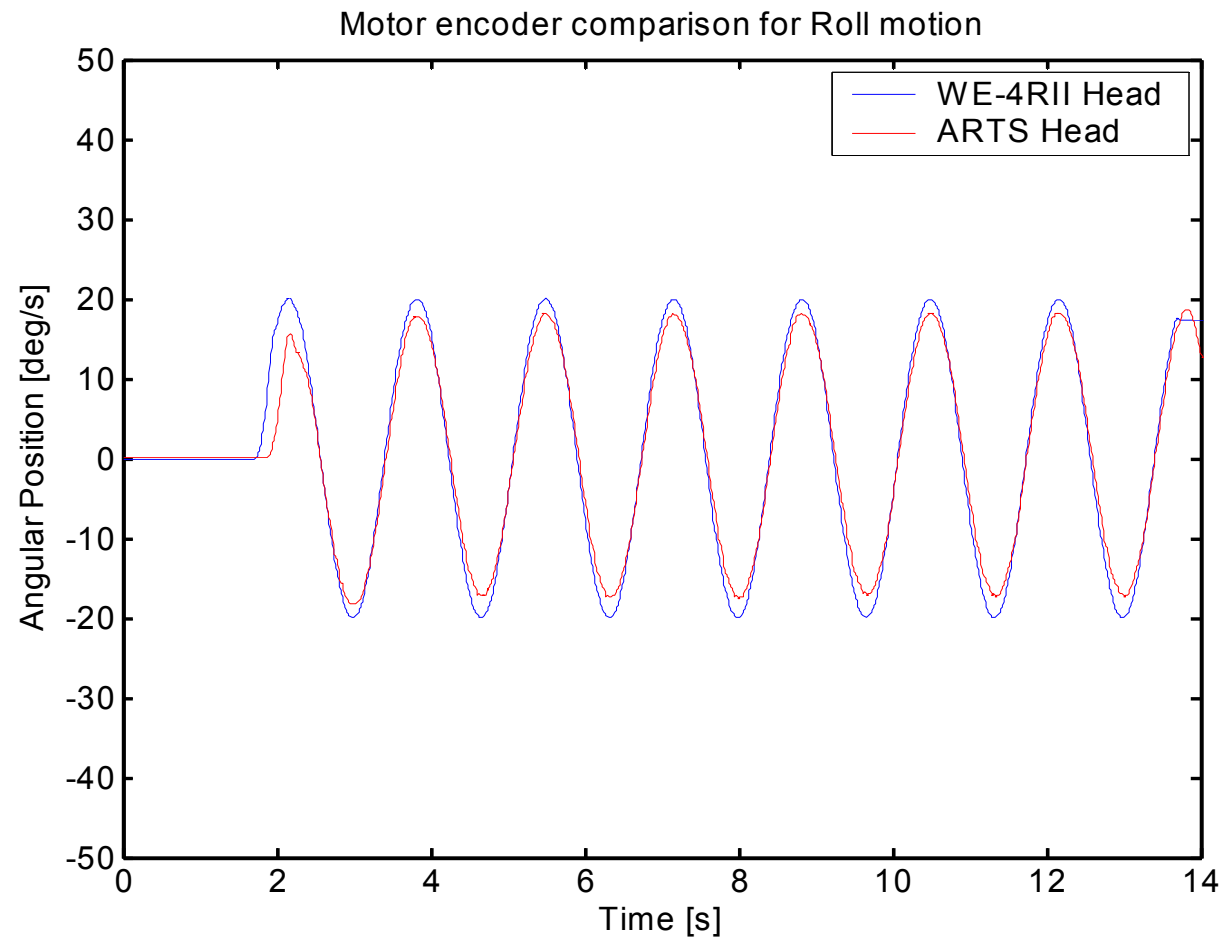
# Motor encoder comparison for Upper Pitch movements



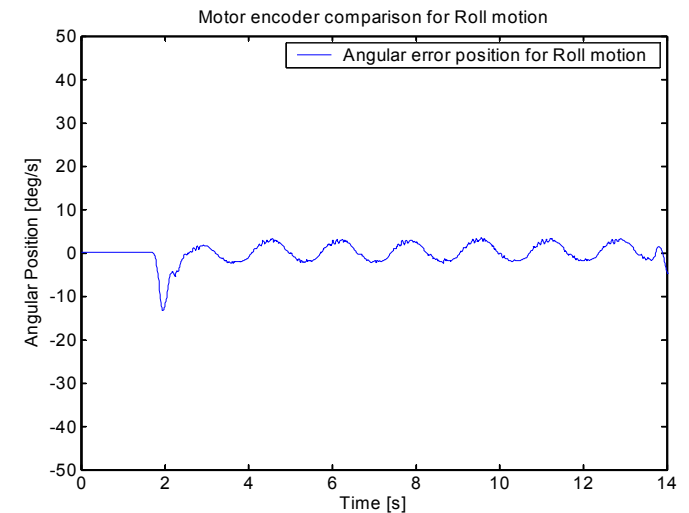
Angular error position during Upper Pitch movements



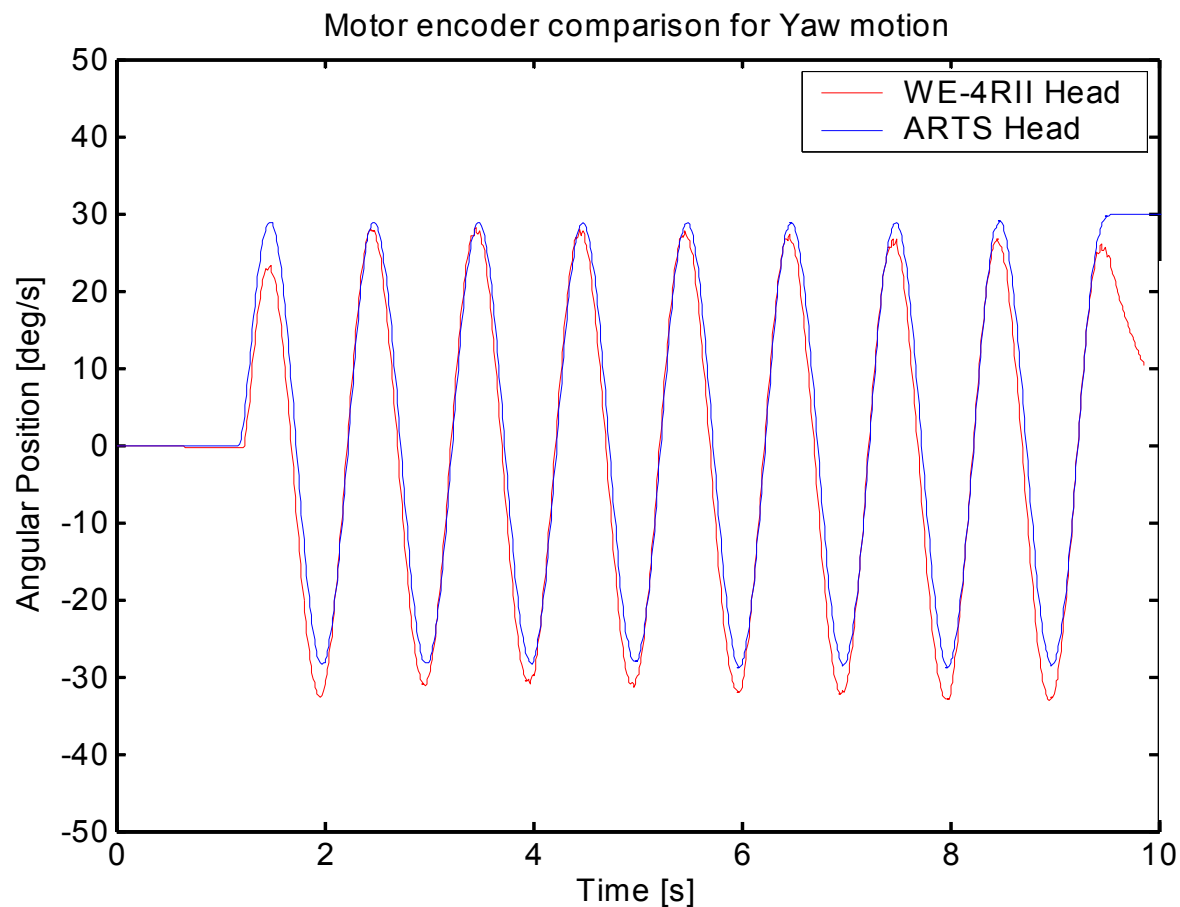
# Motor encoder comparison for Roll movements



## Angular error position during Roll movements



# Motor encoder comparison for Yaw movements



## Angular error position during Yaw movements

