Sensor fusion for motion processing and visualization

Ali Baharev
University of Vienna
19 PUBLICATIONS **71** CITATIONS

Sensor fusion for motion processing and visualization

Ali Baharev, PhD

TÁMOP 4.2.2 “Szenzorhálózat alapú adatgyűjtés és információfeldolgozás” workshop
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What we have - Shimmer Wireless Sensor Platform

Sensors

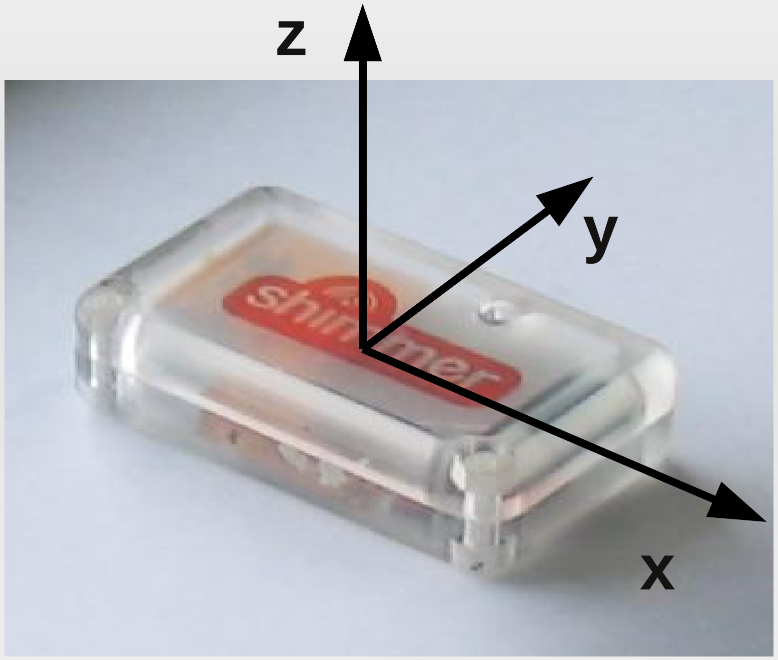
- 3-axis accelerometer, Freescale MMA7260Q ±1.5/2/4/6g (1g≈9.81m/s^2)
- 3-axis gyroscope; two integrated dual-axis angular rate gyroscopes InvenSense 500 series
- No compass

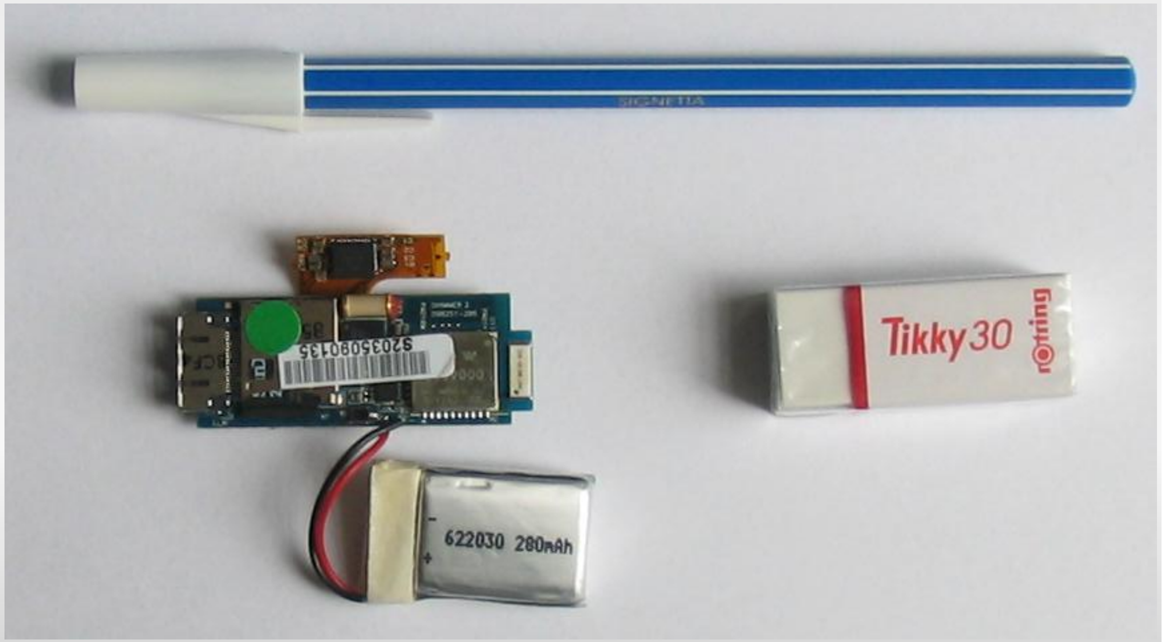
Processing

- MSP430™16-bit Ultra-Low Power MCU @ 8 MHz
- 10Kbyte RAM, 48Kbyte ROM
- 8 Channels of 12bit A/D

Battery

- Integrated Li-ion 280 mAh, 3.7 V





What we have - Shimmer Wireless Sensor Platform (continued)

Radios
- 2.4 GHz IEEE 802.15.4 Chipcon CC2420
- Mitsumi WML-C46N CSR based Class 2 Bluetooth Radio

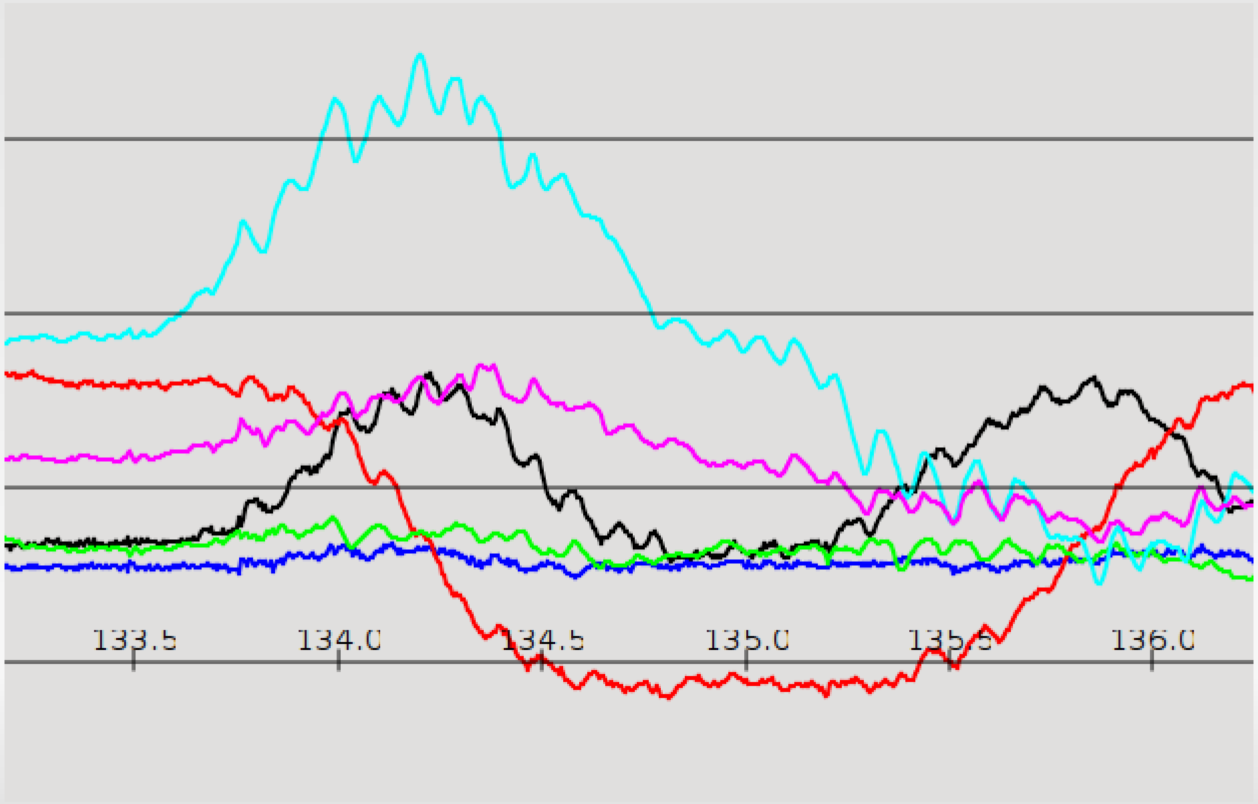
Storage
- 2 GB Micro SD card

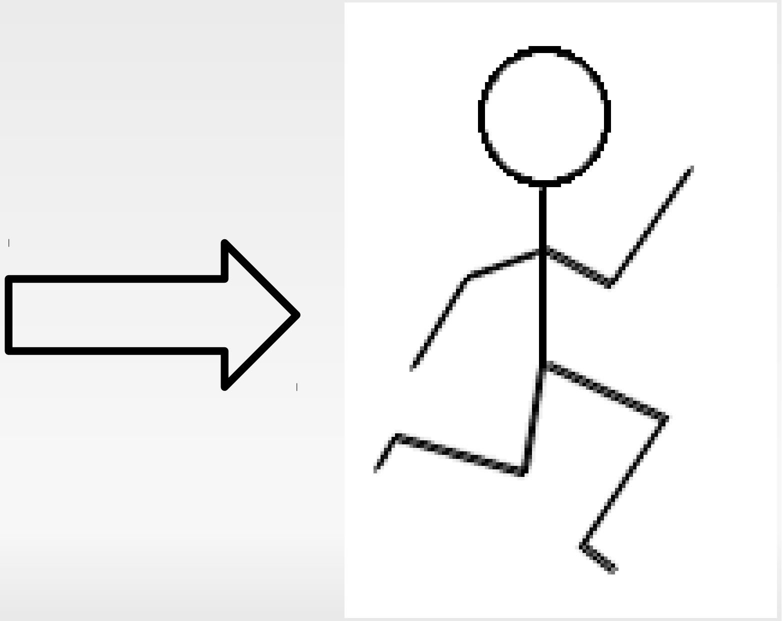
Form factor
- Small form factor
- 50mm x 25mm x 12.5mm
- Light weight: 15 grams

Software
- TinyOS event driven OS for WSN
- Open source

What we want - Gait analysis

- Analysis of measurable parameters of human gait
- From the output of the sensors –> reconstruct the orientation of the limbs in time
- The orientation, described by angles and position





Showing live demo

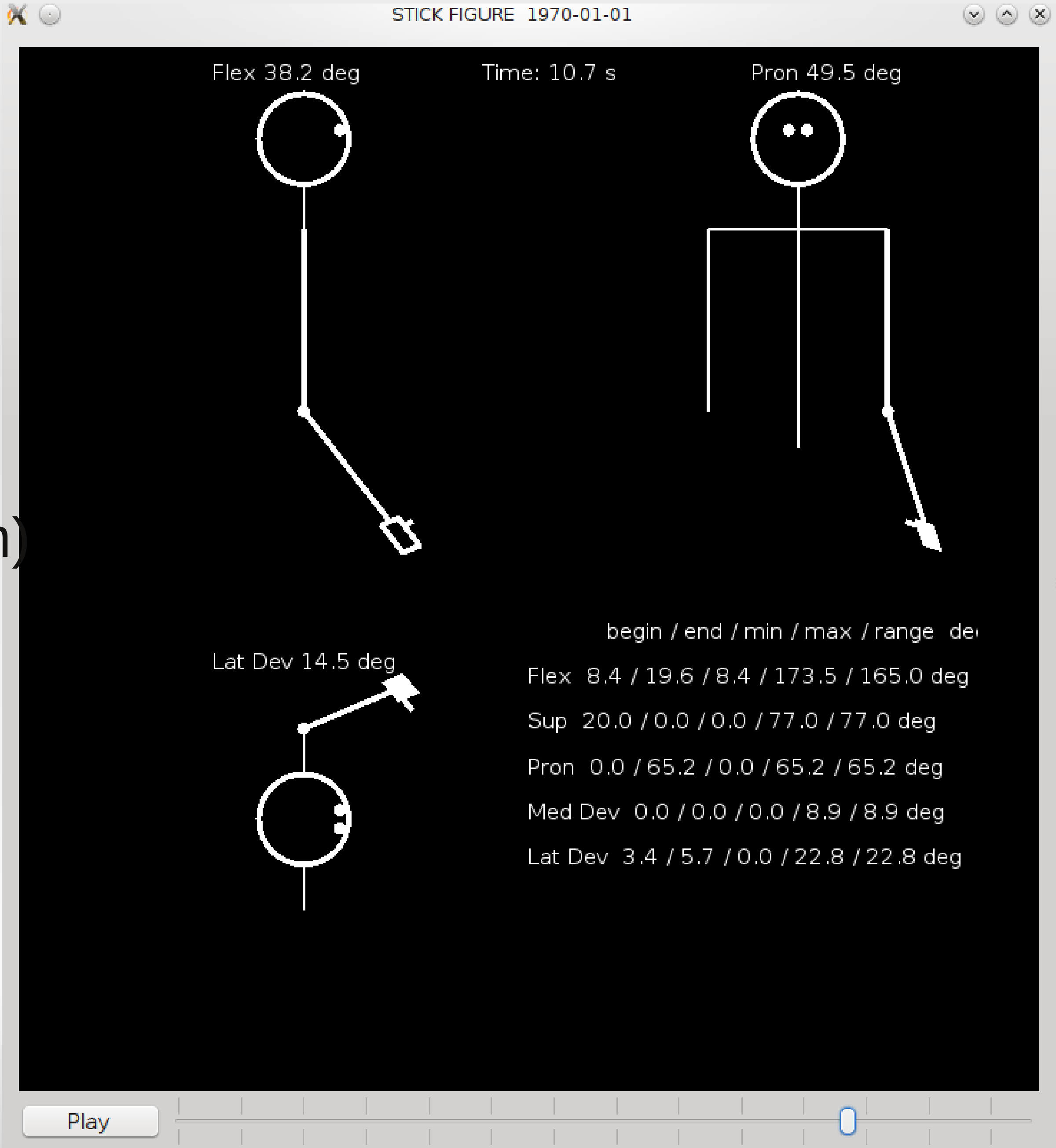
Qt cross-platform GUI,
C++ programming language

Open-source

For medical use (research)

Elbow flexion (left and right arm)

Results are presented as animation (OpenGL)



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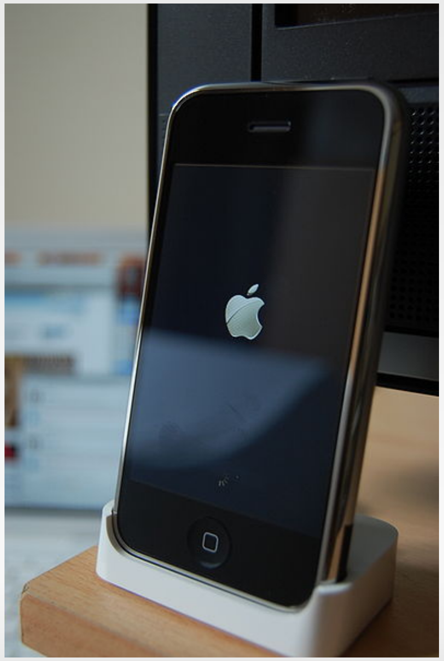
Flex  8.4 / 19.6 / 8.4 / 173.5 / 165.0 deg
Sup  20.0 / 0.0 / 0.0 / 77.0 / 77.0 deg
Pron  0.0 / 65.2 / 0.0 / 65.2 / 65.2 deg
Med Dev  0.0 / 0.0 / 0.0 / 8.9 / 8.9 deg
Lat Dev  3.4 / 5.7 / 0.0 / 22.8 / 22.8 deg
```

What is the competitive edge of the Shimmer platform?

Competitive if:

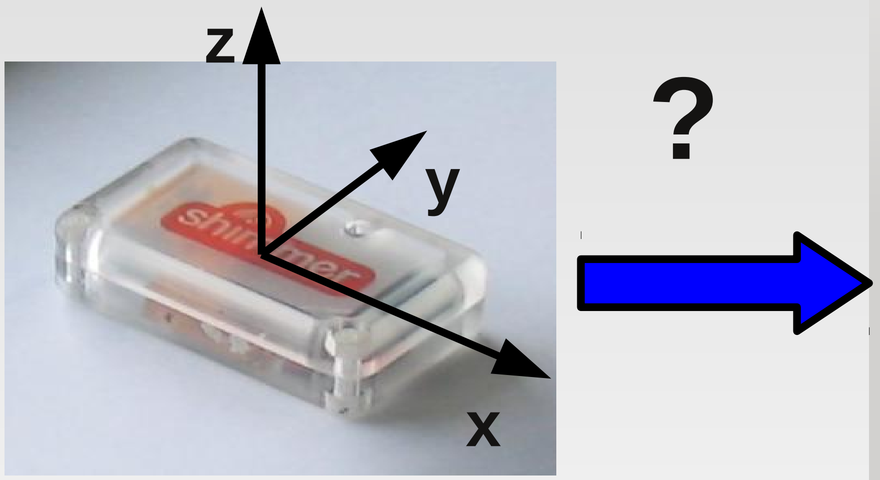
- Video cameras / ultrasound measuring systems are not applicable; for example outdoor activities
- Multiple sensors are needed
- We cannot or we do not want to process the data real-time

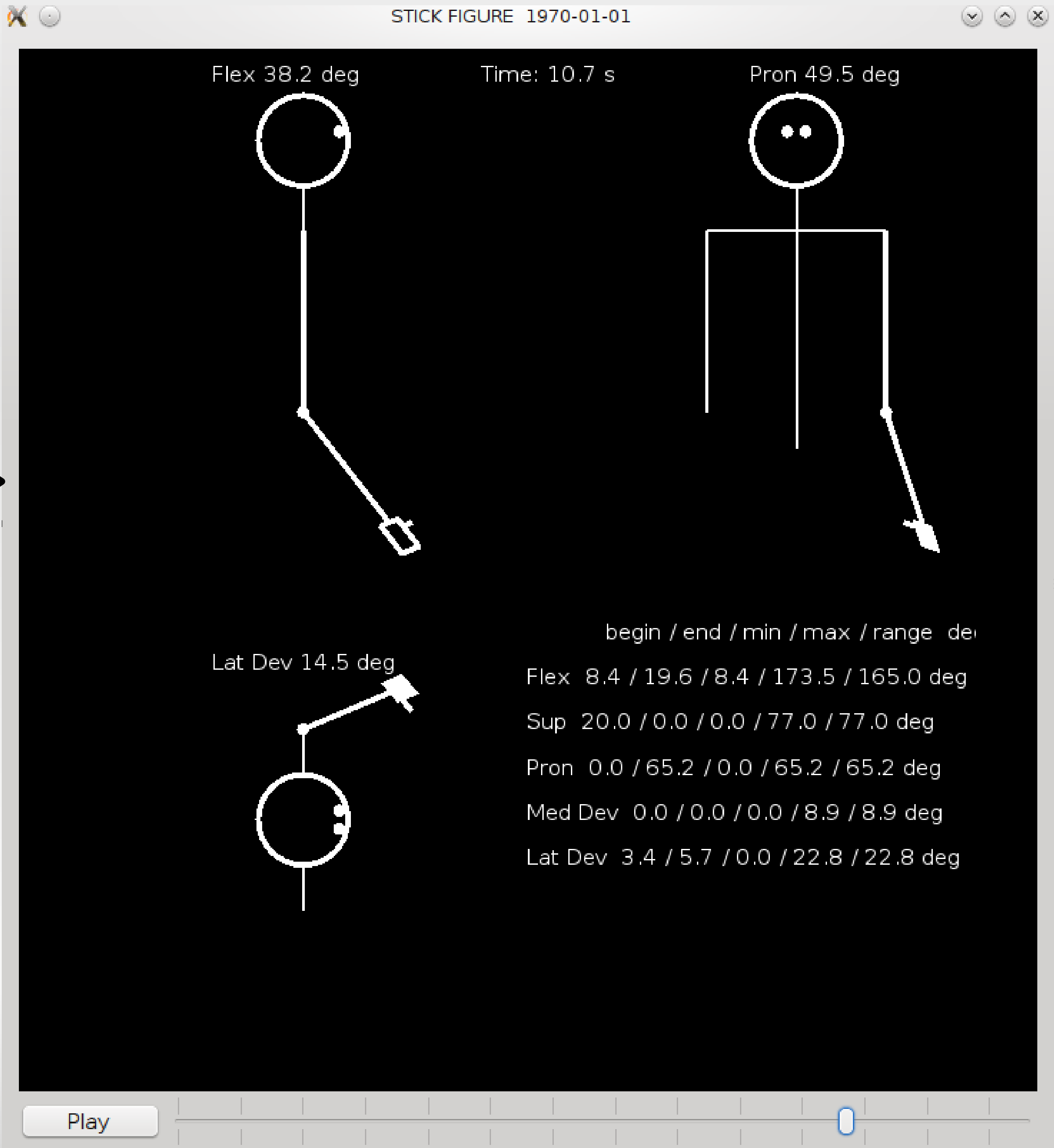
Kinect
Guiness record, 8m in 2months



Smart phones, Android devices

So how can we compute it?





Flex 38.2 deg   Time: 10.7 s   Pron 49.5 deg

Lat Dev 14.5 deg

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          begin / end / min / max / range  de
Flex  8.4 / 19.6 / 8.4 / 173.5 / 165.0 deg
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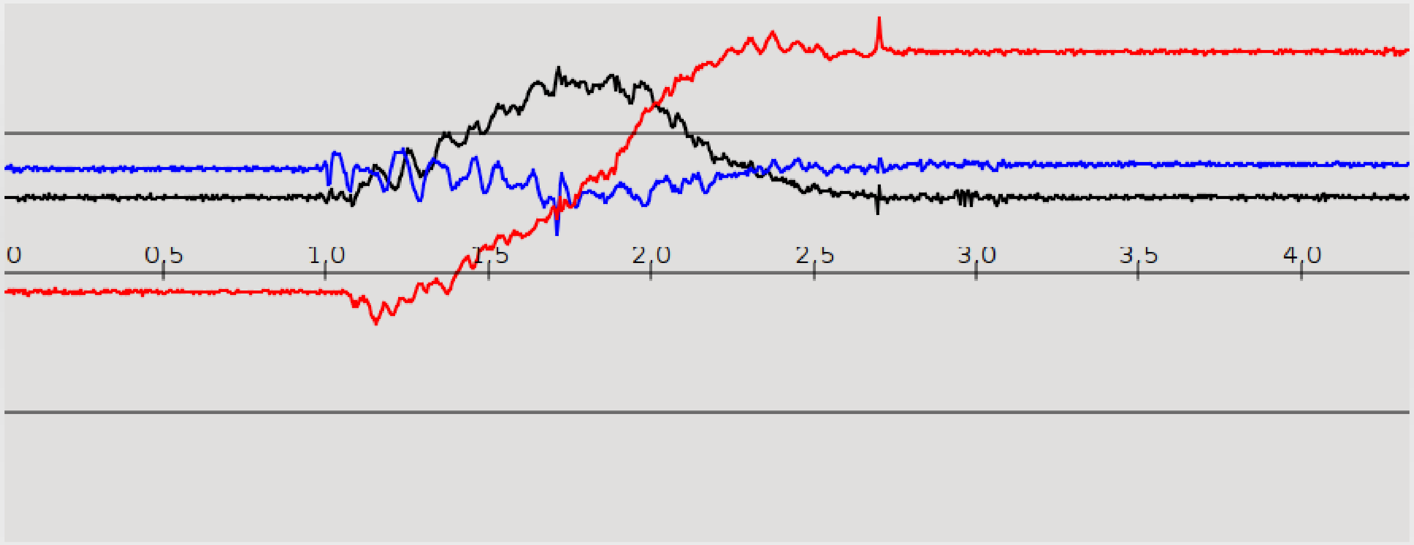
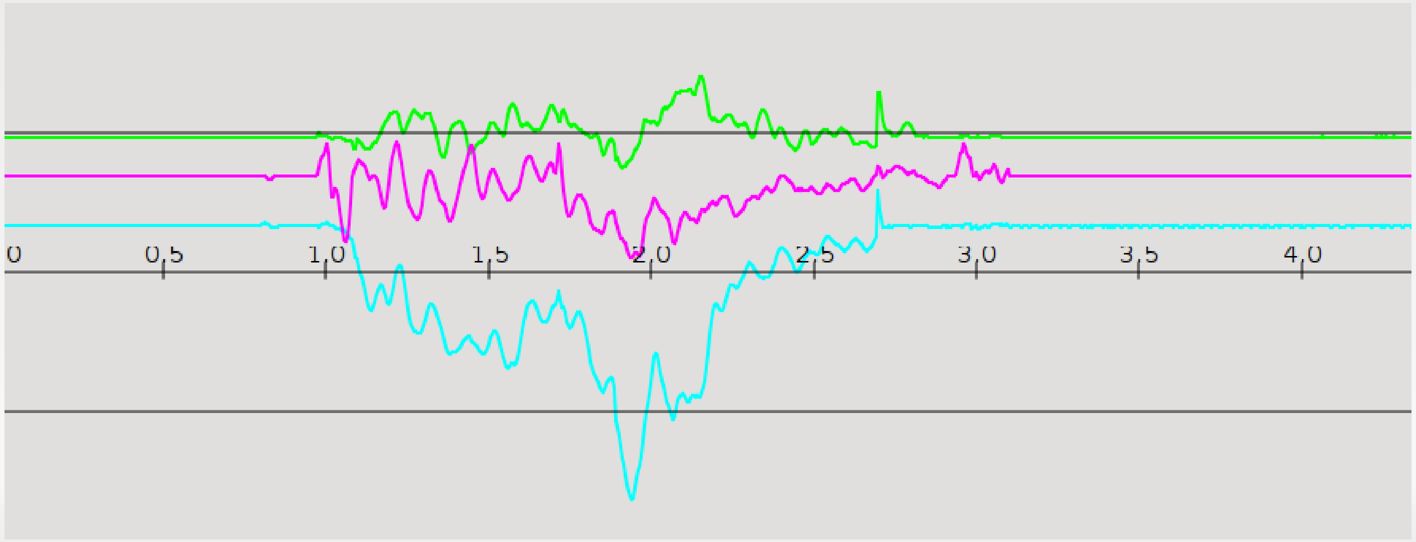
From the output of the sensors –> reconstruct the orientation of the limbs in time

What does the output of the sensors look like?



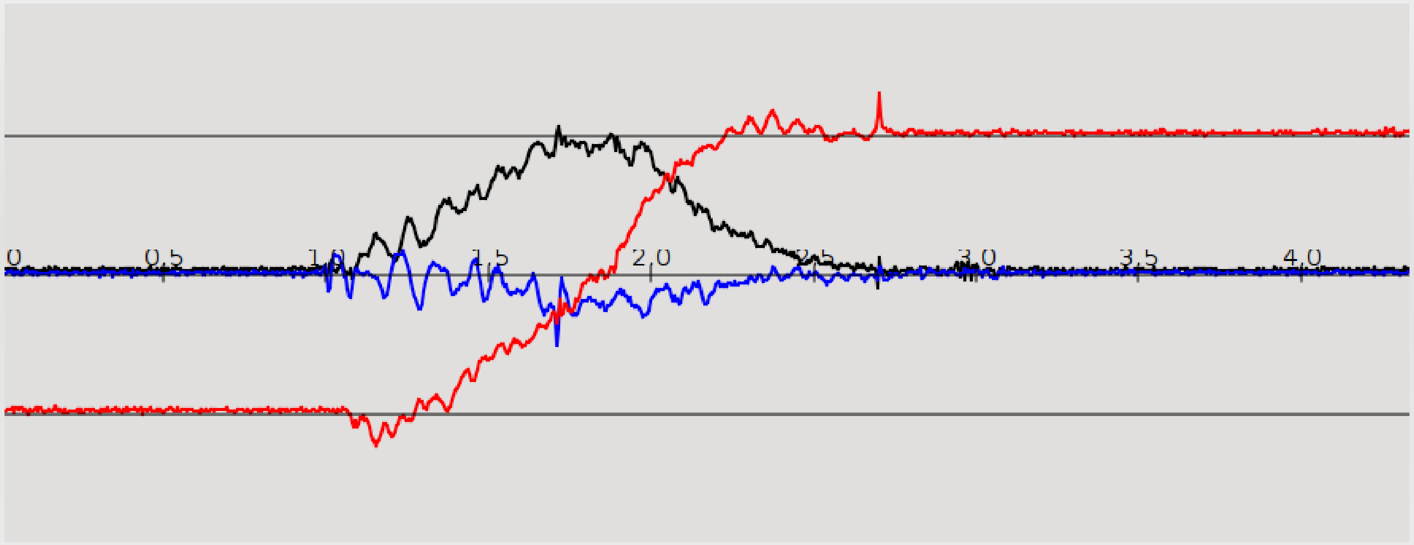
Raw accelerometer data



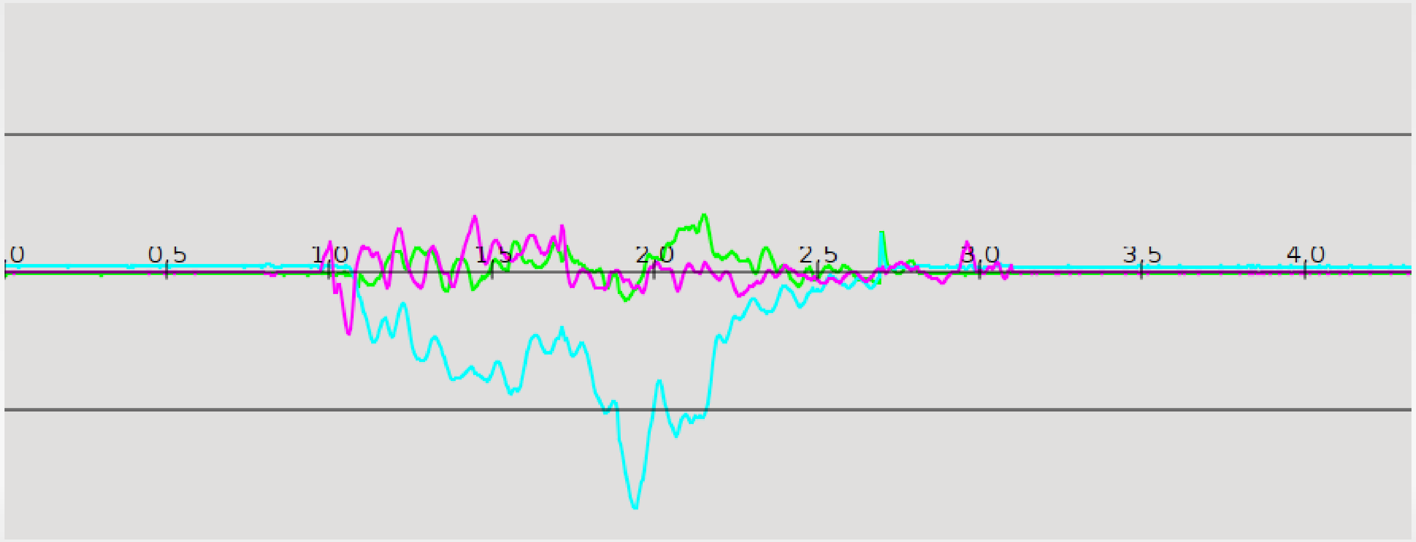
Raw gyroscope data

- The sensor was placed on the desktop then turned over
- Output is not zero even in the static case
- Axes are not neces-sarily perpendicular
- Needs calibration, **linear transfer func-tion** is assumed
- Accelerometer mea-sures gravity even if the mote is stationary

What does the output of the sensors look like?



Calibrated accelerometer data



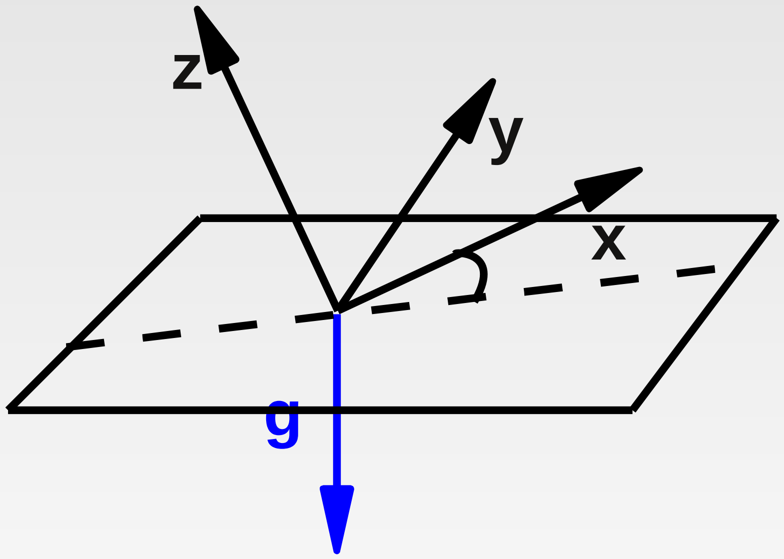
Calibrated gyroscope data

- The sensor was placed on the desktop then turned over
- Output is not zero even in the static case
- Axes are not necessarily perpendicular
- Needs calibration, **linear transfer function** is assumed
- Accelerometer measures gravity even if the mote is stationary

What can we compute from acceleration?

In the static case constant 1g pointing downwards is measured

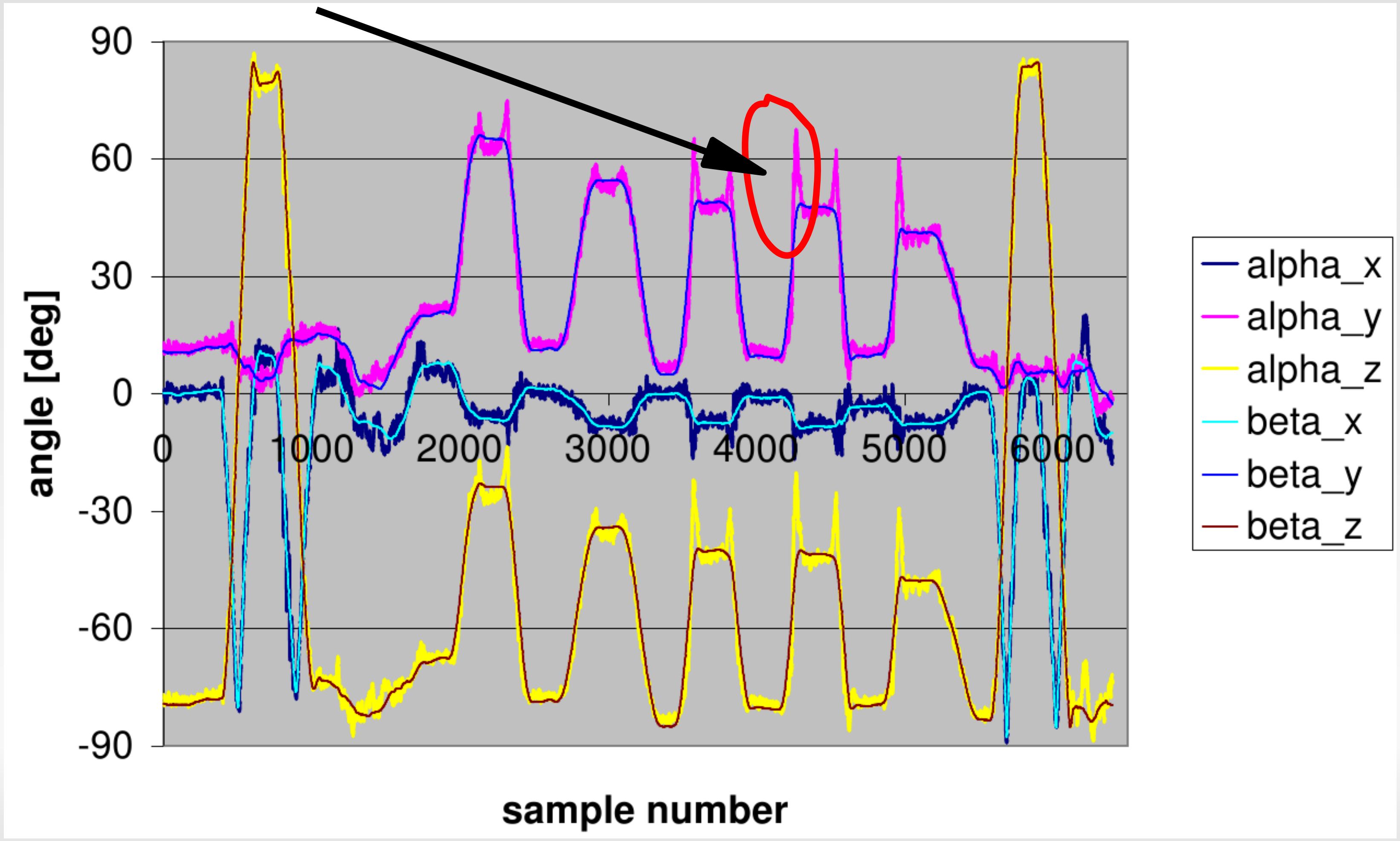
The angle between an axis of the device and the horizontal plane can be computed – **Tilt angles**



We could even compute orientation if we had a compass (accelerometers have no idea where north is)

Tilt angles computed from the acceleration data

Tilt angles computed from the measured acceleration (alpha) practically coincides with the true tilt angles (beta) if the mote is not accelerating
We get weird **spikes** when the sensor is accelerating



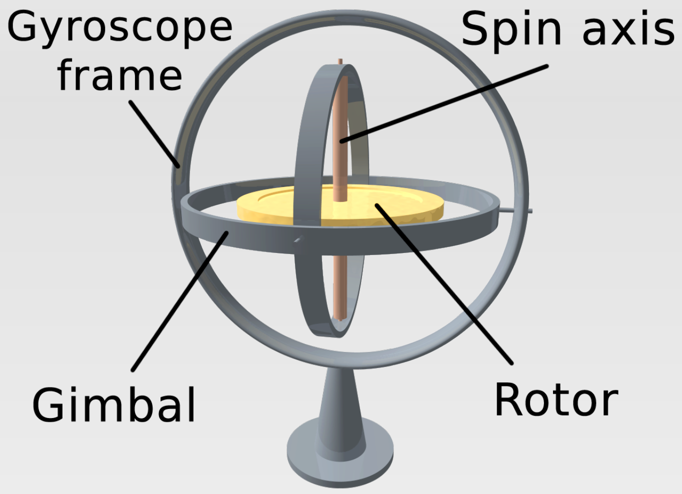
Workaround: **low-pass filter**, works but poor transient response, **lags**

What can we compute from the gyro data?

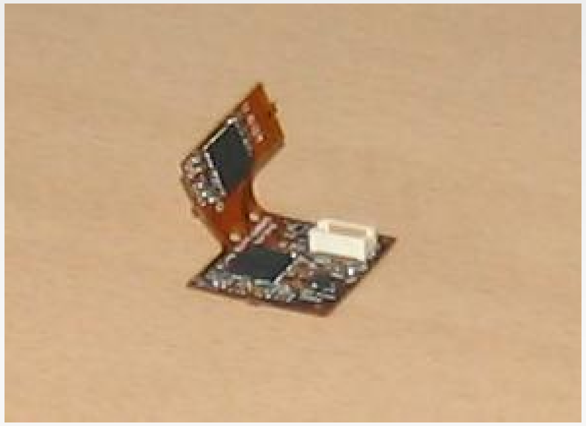
Gyroscopes measures angular rate in the **mote frame** of reference

Angles can be computed by numerical **integration**:

$$\theta(t)=\theta(0)+\int_0^t \omega(\tau)\,d\tau$$ (simplified!)



Good news: not influenced by acceleration or gravity; fast, responsive, not subject to lag
Orientation s.t. initial orientation can be computed



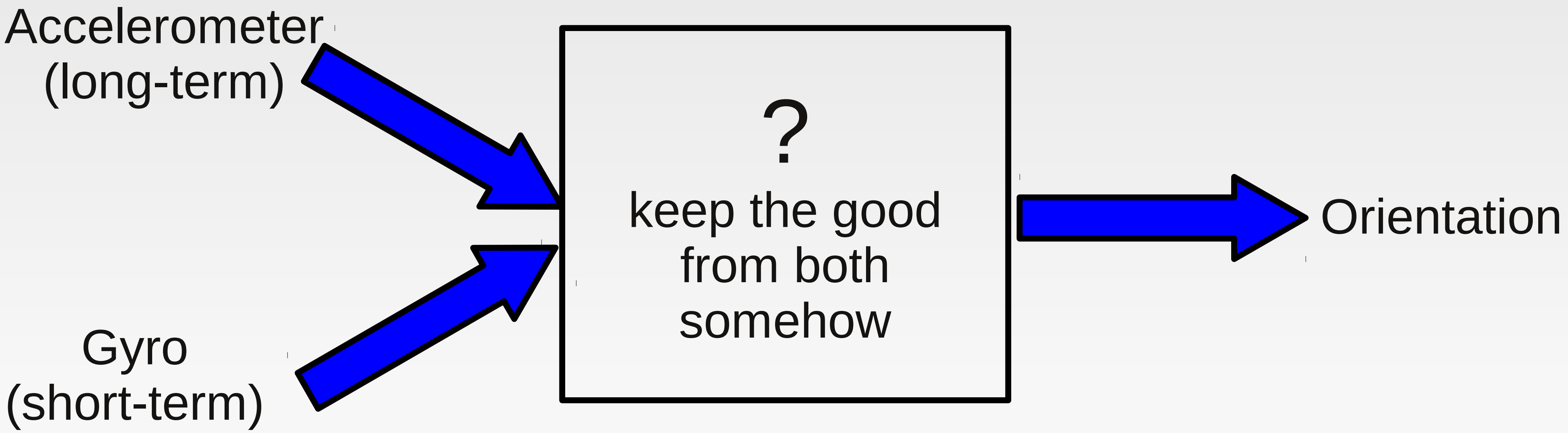
Drift
The integrated effects over time of a slowly varying offset and noise. The drift must be eliminated, requires an external reference vector that does not drift.

Putting it all together – drift cancellation

Both accelerometer and gyro data can be used to **compute angles**

Accelerometer provides a reference vector, gravity, that does not drift (long-term) but has poor transient response

Gyro data is excellent for computing orientation (short-term), gives fast transient response but needs reference vector that does not drift



Our approach: offline, nonlinear regression for each record
Custom C++ solver using IPOPT

Future plans

Appropriate uses:

- Outdoor activities
- Multiple sensors
- Off-line processing

Plans:

- Rowing
- Running

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Prof. László Hatvani: technical discussion

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Miklós Maróti: supervising the research

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References

W. Premerlani and P. Bizard; *Direction Cosine Matrix IMU: Theory*
http://gentlenav.googlecode.com/files/DCMDraft2.pdf

Shane Colton; *The Balance Filter, A Simple Solution for Integrating Accelerometer and Gyroscope Measurements for a Balancing Platform*; Chief Delphi white paper, 2007.
http://web.mit.edu/scolton/www/filter.pdf

Further slides, not presented

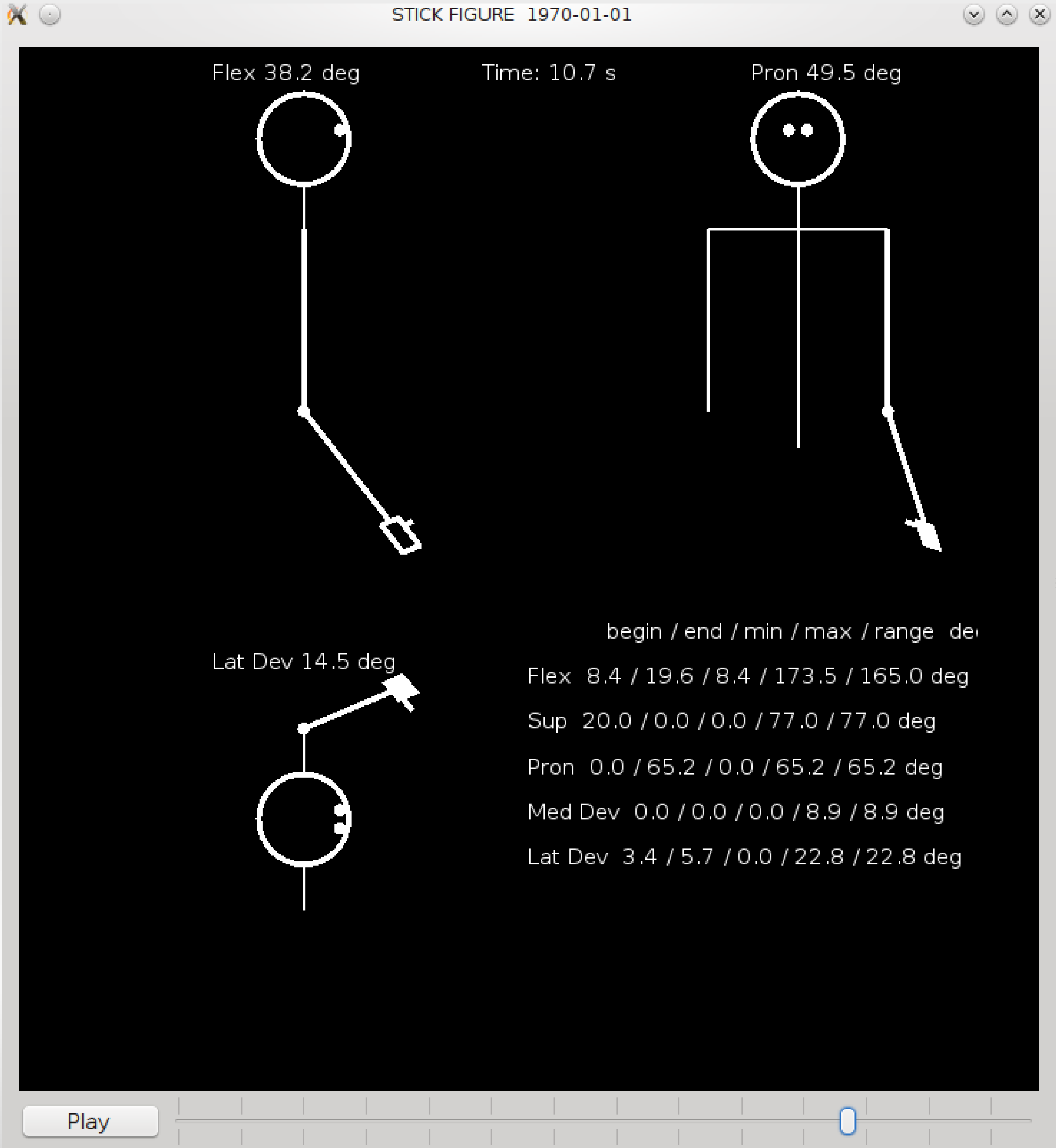
Live demo – fooling the application

After drift cancellation, only the gyro data is used to compute orientation

Position is not computed

We can fool the application by rotating the sensor around a point

It still gives us a proper elbow flexion



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Lat Dev  3.4 / 5.7 / 0.0 / 22.8 / 22.8 deg
```
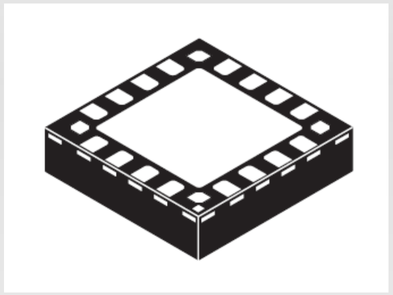
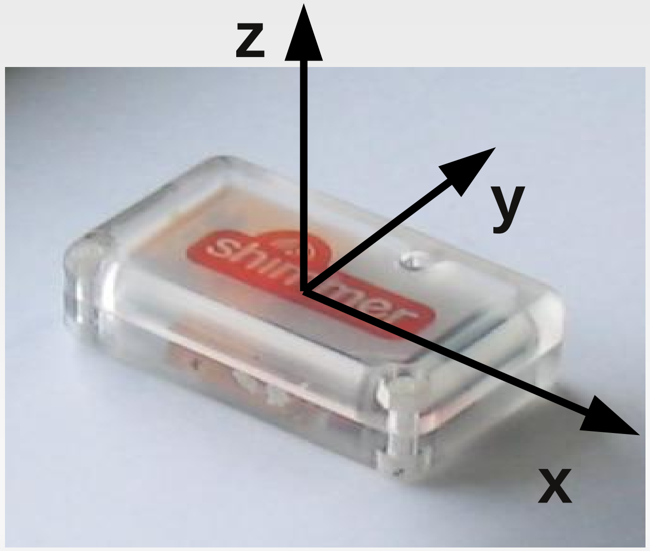
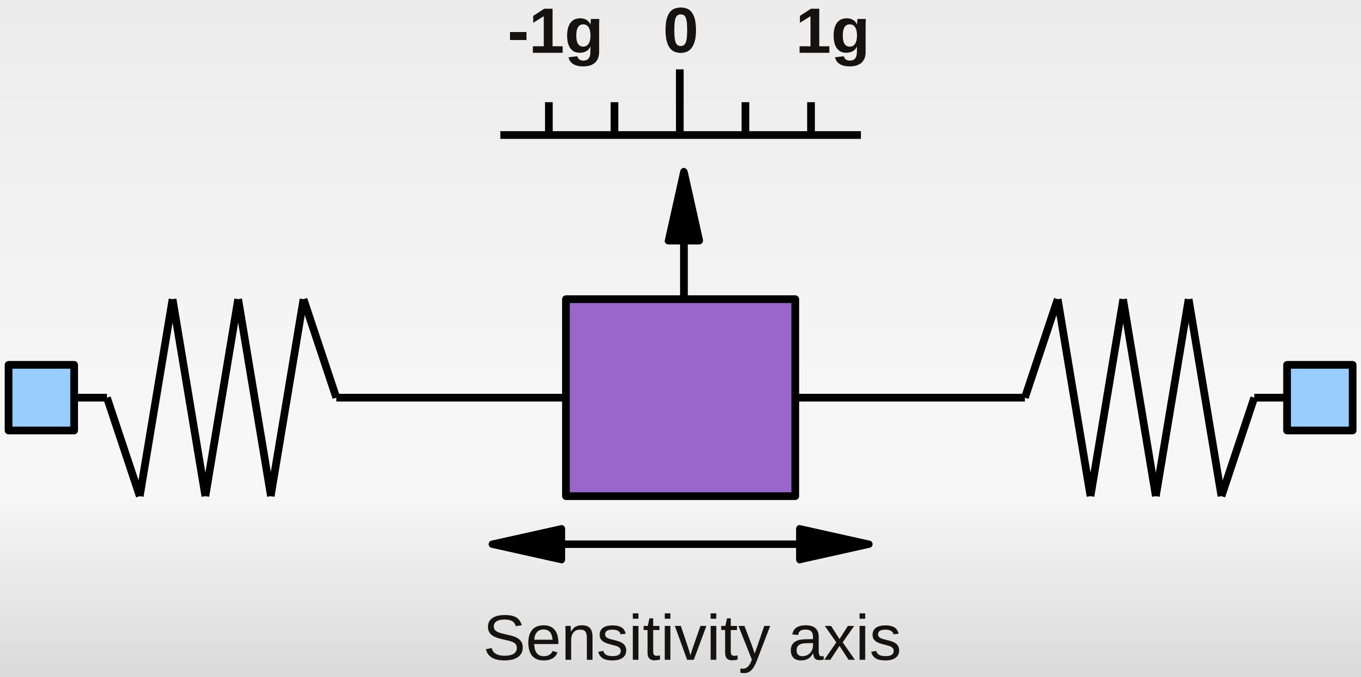

Sensors: accelerometer

Accelerometer

- 3 Axis Accelerometer, Freescale MMA7260Q
- Sensitivity: 800 mV/g @ 1.5g
- 12 bit analogue digital converter –> integer number
- Resolution: $(1.5g+1.5g)/(2^{12}) \approx 7 \cdot 10^{-4}$ g/unit

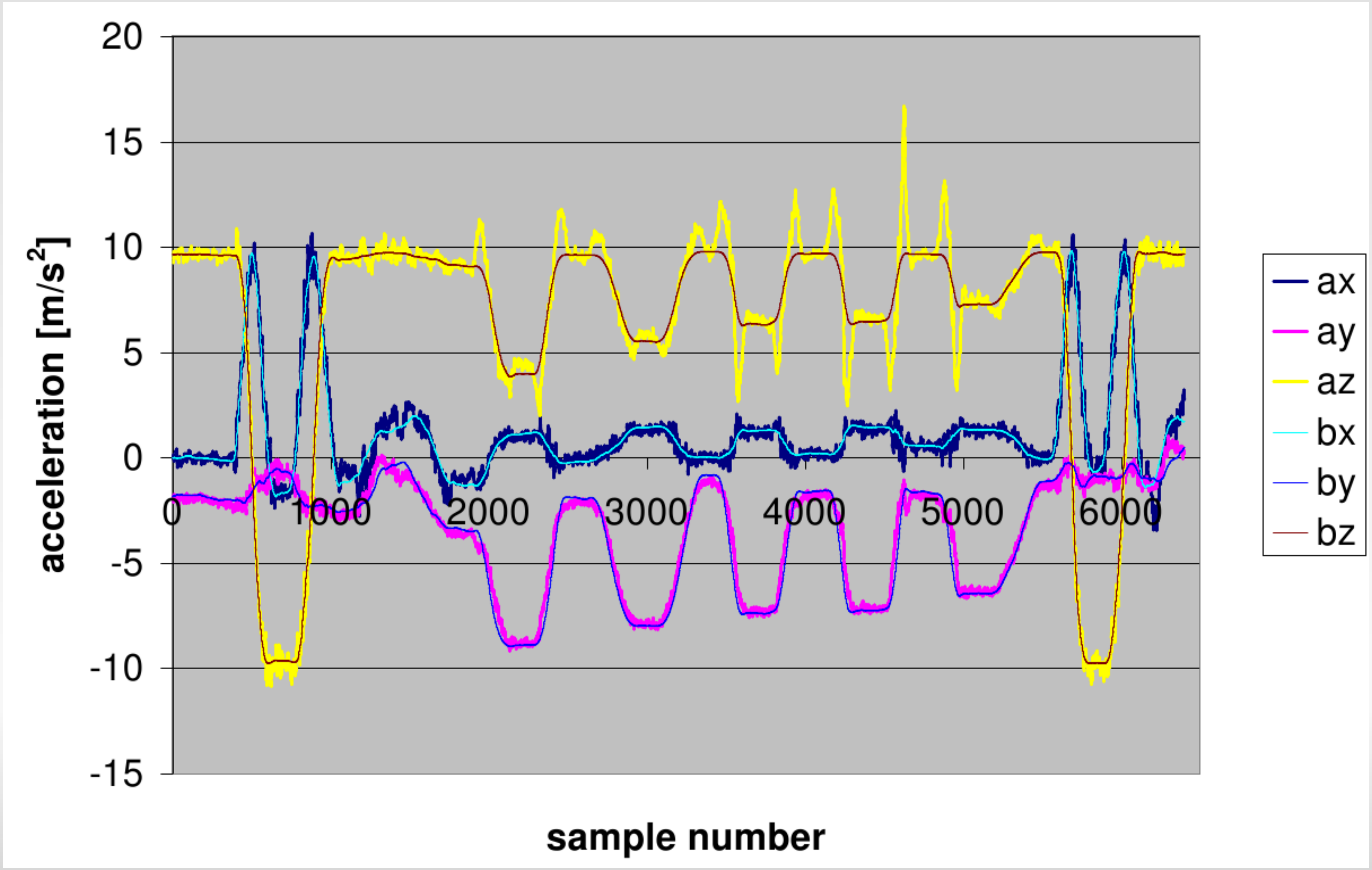






Accelerometer measures gravity + acceleration

Comparing the measured acceleration (ax, ay, az) and the gravitational acceleration (bx, by, bz) in the mote frame
Workaround: **low-pass filter**, works but poor transient response, **lag**



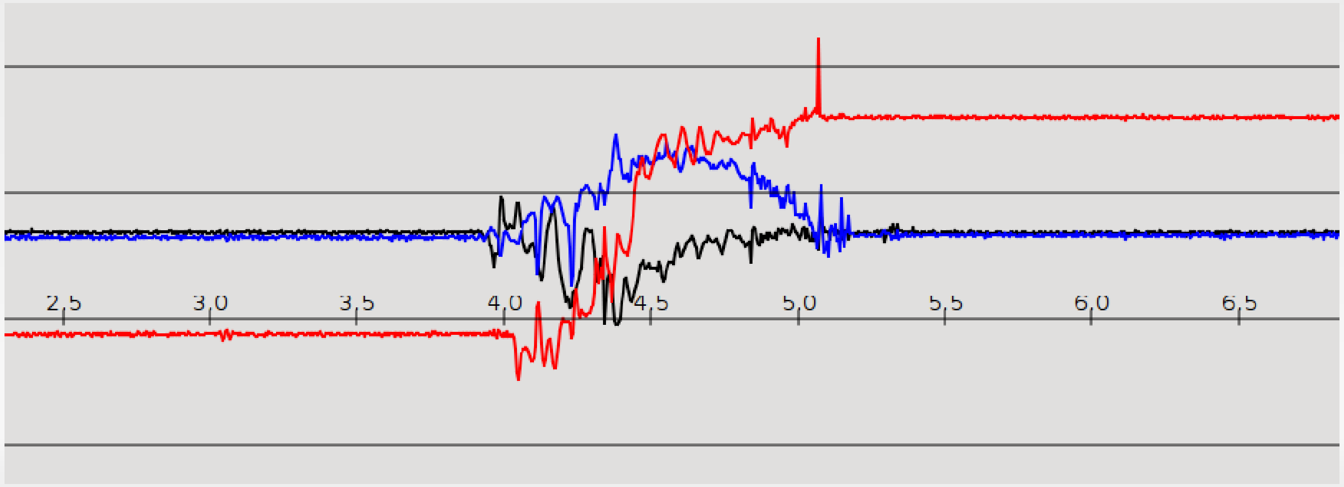
Static calibration of the accelerometer

Assumption: measured value is a linear function of the acceleration (linear transfer function)

Calibration: find the gain matrix (9 unknowns) and offset vector (3 unknowns)

acceleration [m/s^2] = gain·(measured value) − offset

Place the mote on each of its six side and record the output acceleration: (±1g, 0, 0); (0, ±1g, 0); (0, 0, ±1g)

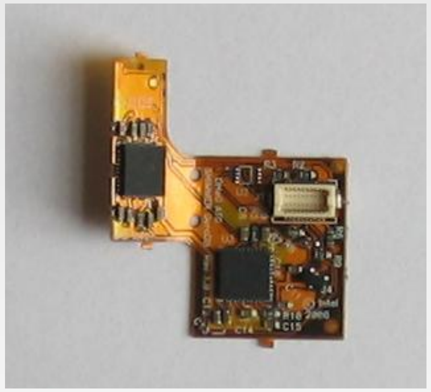


Gives an overdetermined system of linear equations (18 equations and 12 unknowns); linear least-squares, analytic solution (SVD)

Sensors: accelerometer and gyroscopes

Accelerometer
- 3 Axis Accelerometer, Freescale MMA7260Q
- Sensitivity: 800 mV/g @ 1.5g
- 12 bit analogue digital converter –> integer number
- Resolution: $(1.5\mathrm{g}+1.5\mathrm{g})/(2^{12})\approx 7\cdot 10^{-4}\,\mathrm{g/unit}$

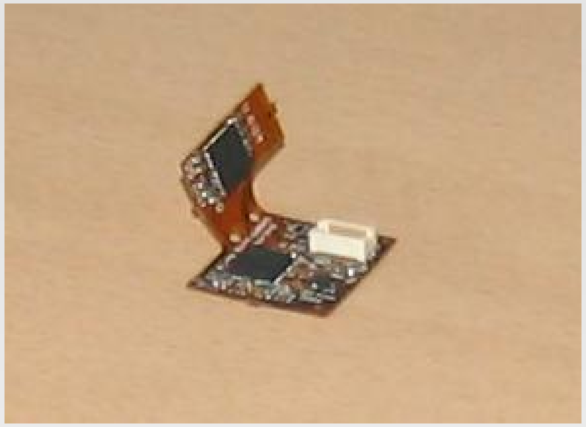
Gyroscope
- 2 integrated dual-axis, InvenSense 500 series
- Full scale range: +/- 5000 deg/s
- Sensitivity: 2 mV/deg/s



Output in the static case
- Offset (**not zero**), actual value depends mainly on chip, plus temperature, *etc.*
- Accelerometer: constant value corresponding to 1g (gravity of Earth)

Sensors: gyroscopes

Gyroscope
- 2 integrated dual-axis, InvenSense 500 series
- Measures angular rate
- Full scale range: +/- 5000 deg/s
- Sensitivity: 2 mV/deg/s
- 12 bit ADC –> integer number



Output in the static case
- Offset (**not zero**), actual value depends mainly on chip, plus temperature, *etc.*
- Accelerometer: constant value corresponding to 1g (gravity of Earth)

Calibration of the gyroscopes

Calibration: find the gain matrix (9 unknowns) and
offset vector (3 unknowns; linear transfer function)

angular rate [rad/s] = gain·(measured value) − offset

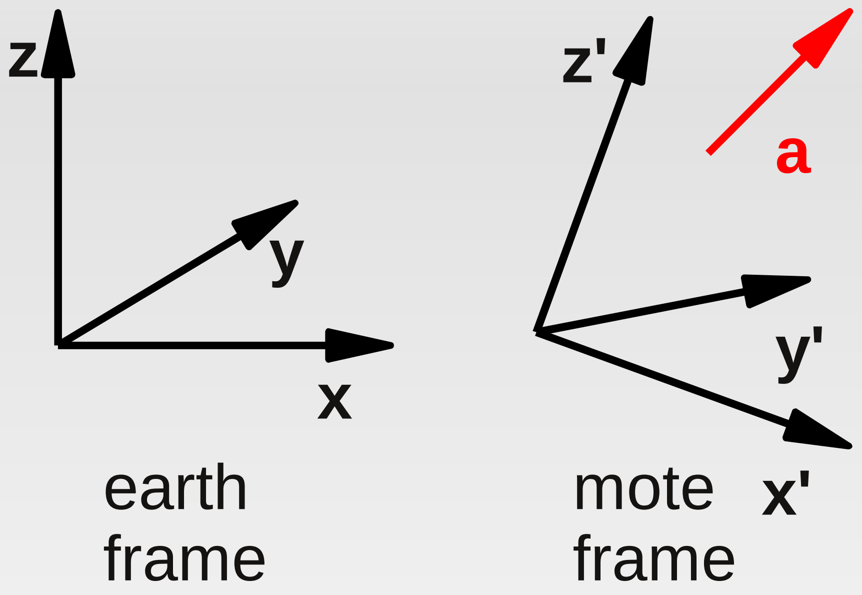
Place the mote on each of its six side and record the output angular rate: (±45rpm, 0, 0); (0, ±45rpm, 0); (0, 0, ±45rpm)

A small error in the offset accumulates –> huge error in orientation over time, **drift**

Can we compute speed or position from a(t)?

$$v(t)=v(0)+\int_0^t (a(\tau)-g)\,d\tau$$

$$r(t)=r(0)+\int_0^t v(\tau)\,d\tau$$



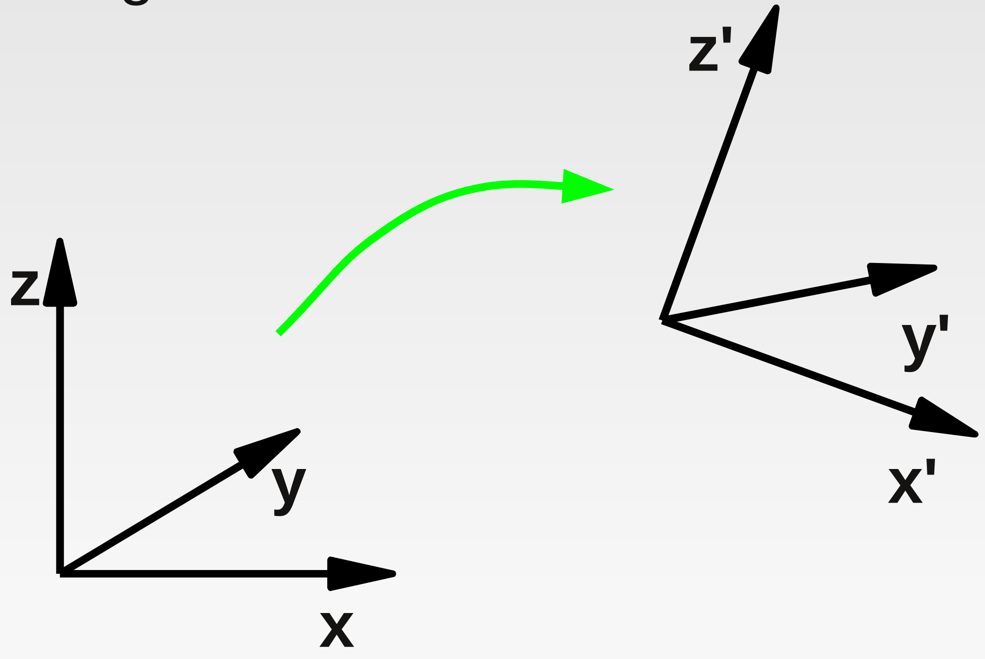
The a(t) vector is measured in the **mote frame** of reference but we would like to track the mote in the **earth frame**.

Transformation is needed from one frame to the other –> **rotation**

Rotation

We need rotation to transforms the acceleration vectors from the mote frame of reference to the earth reference

Rotation: linear transformation, preserves lengths of vectors and angles between vectors



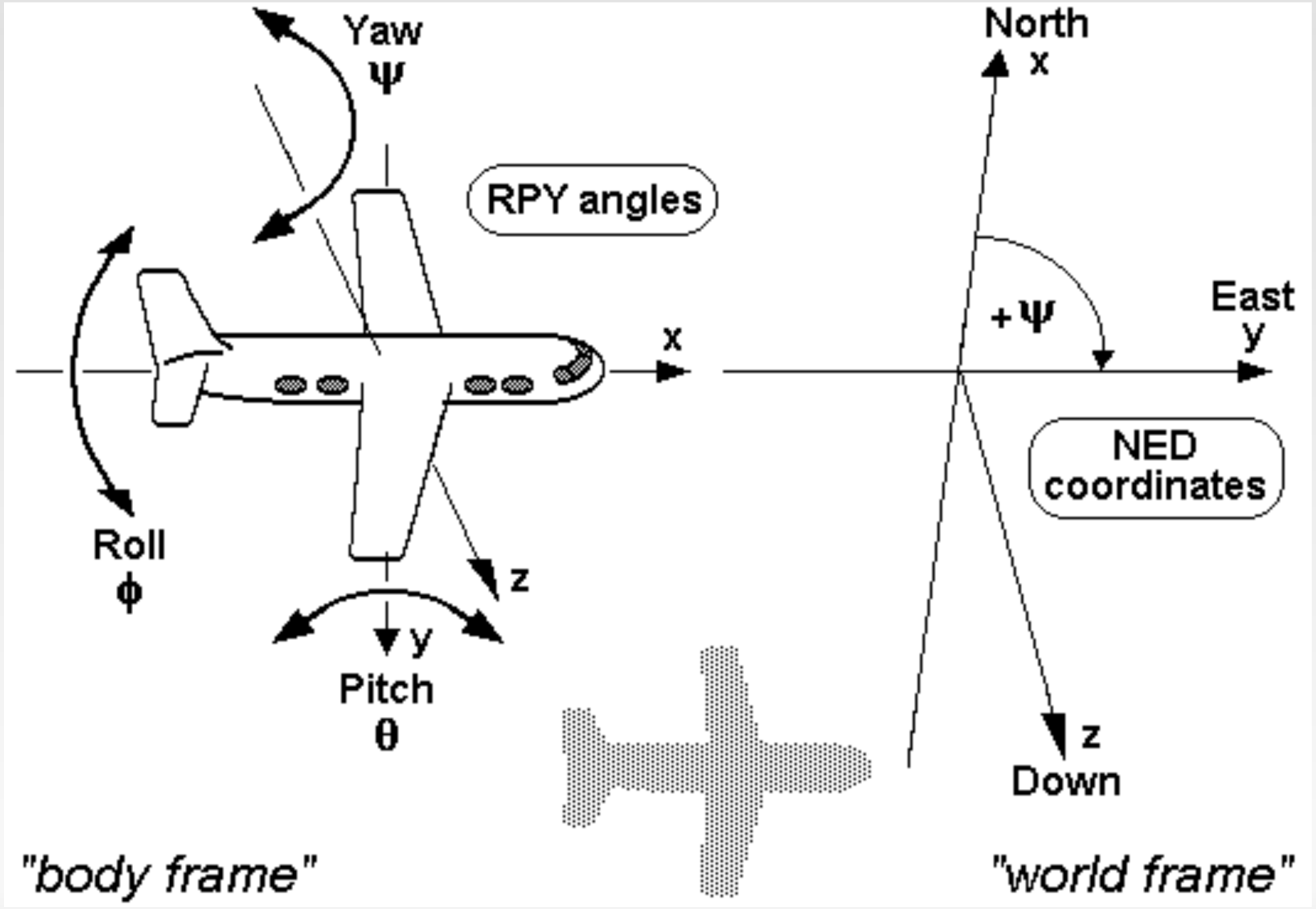
$$\begin{array}{c|ccc} & x & y & z \\ \hline x' & r_{xx'} & r_{yx'} & r_{zx'} \\ y' & r_{xy'} & r_{yy'} & r_{zy'} \\ z' & r_{xz'} & r_{yz'} & r_{zz'} \end{array}$$

Rotation matrix

Rotation (continued)

Rotation representations

- Rotation matrix
- Euler angles
- Angle/axis
- Quaternion



Rotation is uniquely defined by 3 angles

Performance comparisons of rotation methods

Storage requirements

matrix	9
quaternions	4
angle/axis	3

Performance comparison of rotation chaining operations

	multiplies	add/substr.	total
matrix	27	18	45
quaternions	16	12	28

Performance comparison of vector rotating operations

	multiplies	add/substr.	sin/cos	total
matrix	9	6	0	15
quaternions	21	18	0	39
angle/axis	23	16	2	45

Infinitesimal rotations

Rotation in 3D is generally not commutative (neither is matrix multiplication)

The order in which infinitesimal rotations are applied is irrelevant

Rotation matrix of infinitesimal rotations along the x, y, z axis:

$$\begin{bmatrix} 1 & -d\Theta_z & d\Theta_y \\ d\Theta_z & 1 & -d\Theta_x \\ -d\Theta_y & d\Theta_x & 1 \end{bmatrix}$$

Gives a recipe to update the rotation matrix from gyro signals

Updating the rotation matrix from gyro signals

W. Premerlani and P. Bizard; *Direction Cosine Matrix IMU: Theory*

$$R(t+dt)=R(t)\begin{bmatrix} 1 & -d\Theta_z & d\Theta_y \\ d\Theta_z & 1 & -d\Theta_x \\ -d\Theta_y & d\Theta_x & 1 \end{bmatrix}$$

$$d\Theta_x=\omega_x dt$$
$$d\Theta_y=\omega_y dt$$
$$d\Theta_z=\omega_z dt$$

Sources of errors

- Finite time step
- Quantization error: finite digital representation

The rotation matrix must be corrected –> **renormalization** at each point (no divisions or square roots)

Drift cancellation off-line with nonlinear regression

Off-line, operates on the whole data set but manipulates only 12 variables: 3x3 gain matrix and offset vector of the gyro

angular rate [rad/s] = gain·(measured value) − offset

Assumption: ‘On average’ the measured acceleration points into the same direction (gravitational acceleration).

A **nonlinear programming problem** is solved

$$\max \left| \sum_{i=0}^{N} R_i a_i \right|$$

$$R(0)=I$$

$$R(i)=R(i-1)G(i-1) \quad \text{for} \quad i=1\dots N$$

$$G(i): \quad \text{from gyro signals}$$

variables: gyro gain and offset

Software

- **NLP**, a nonlinear programming problem to be solved
- **IPOPT**, general purpose NLP solver (line search filter method) remarkably robust
- **C++ API** is used, only the objective has to be implemented
- **Automatic differentiation** (AD): the gradient is not approximated with numerical differentiation but automagically computed with AD (our own C++ library)
- **L-BFGS** (approximates the inverse Hessian matrix) to further speed up the computations

On-line methods for sensor fusion

Perhaps the most popular one is the **Kalman Filter**

It is an on-line method that manipulates each sample

Good introduction with examples: SIGGRAPH Course Pack

Kalman filter is difficult to understand

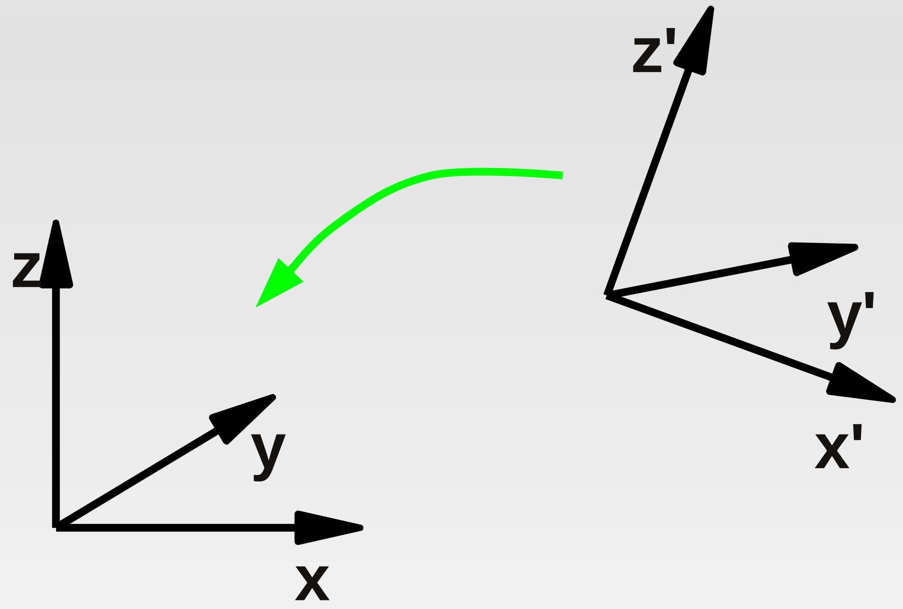
Much simpler approach is the Complementary Filter with similar results (see filter.pdf)

Computing position

Now, the measured values in the mote frame can be transformed to the earth frame

$$v(t) = v(0) + \int_0^t (a(\tau) - g)\, d\tau$$

$$r(t) = r(0) + \int_0^t v(\tau)\, d\tau$$



Horrible error, computing the double integral is notoriously difficult