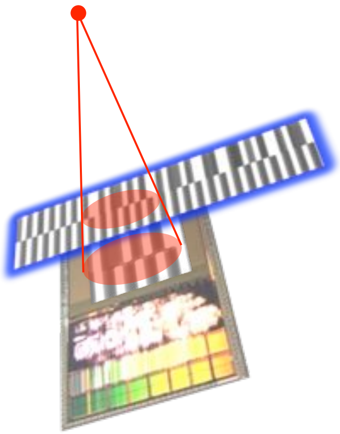
Vision Embedded Systems

CSEM, **SpaceCoder Technology**, June 2013

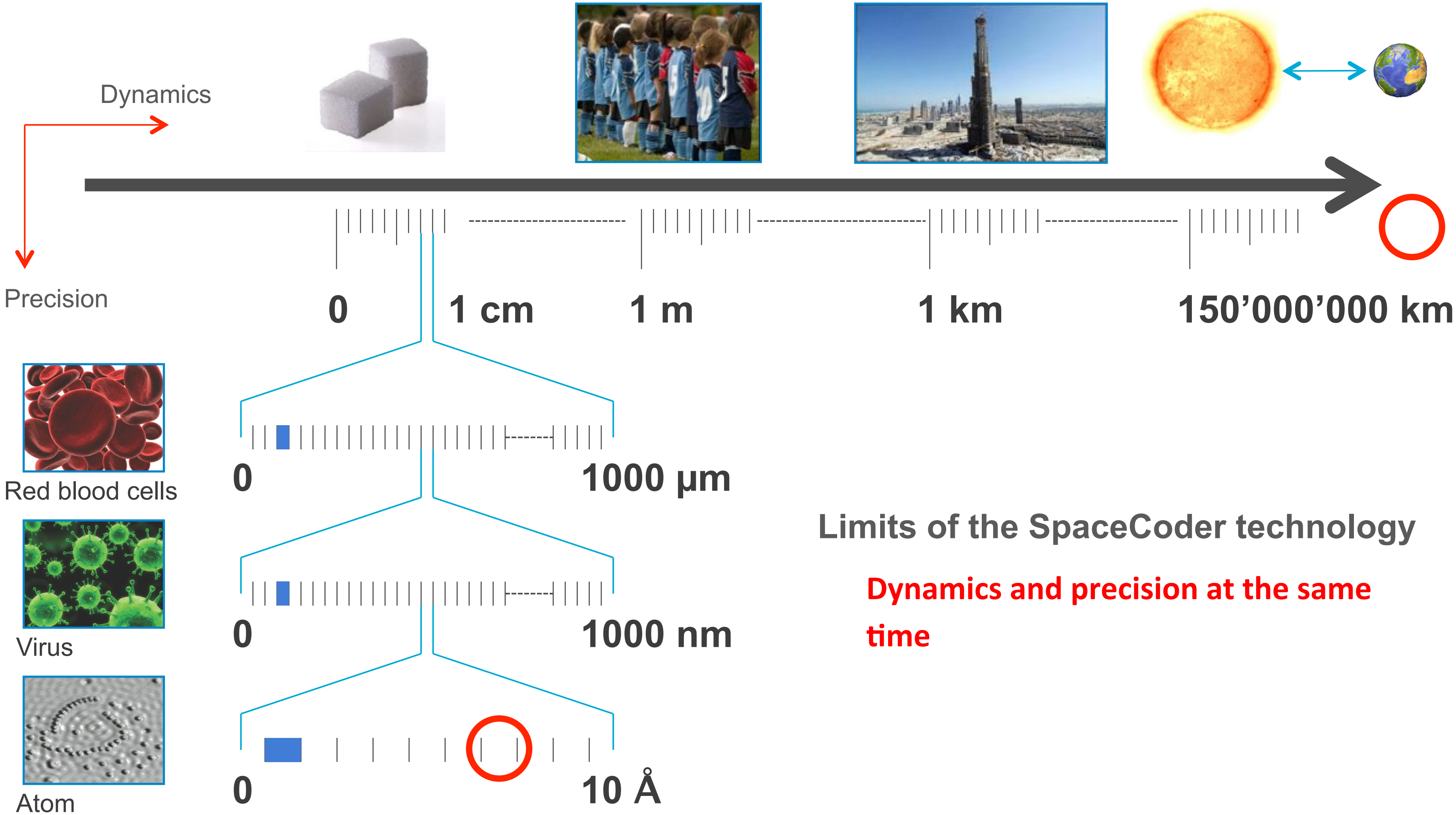


Outline of this presentation

- Birth of a technology: the Electric Power Assist Steering (EPAS) sensor
- Measuring nanometric displacements
- Multidimensional extensions: shadow imaging for 1 DOF to 6 DOF measurements
- Vision & microelectronic technologies: the perfect matching
- Examples: airplane weight balance, optical accelerometers and 6 DOF pointers
- Conclusion

SpaceCoder

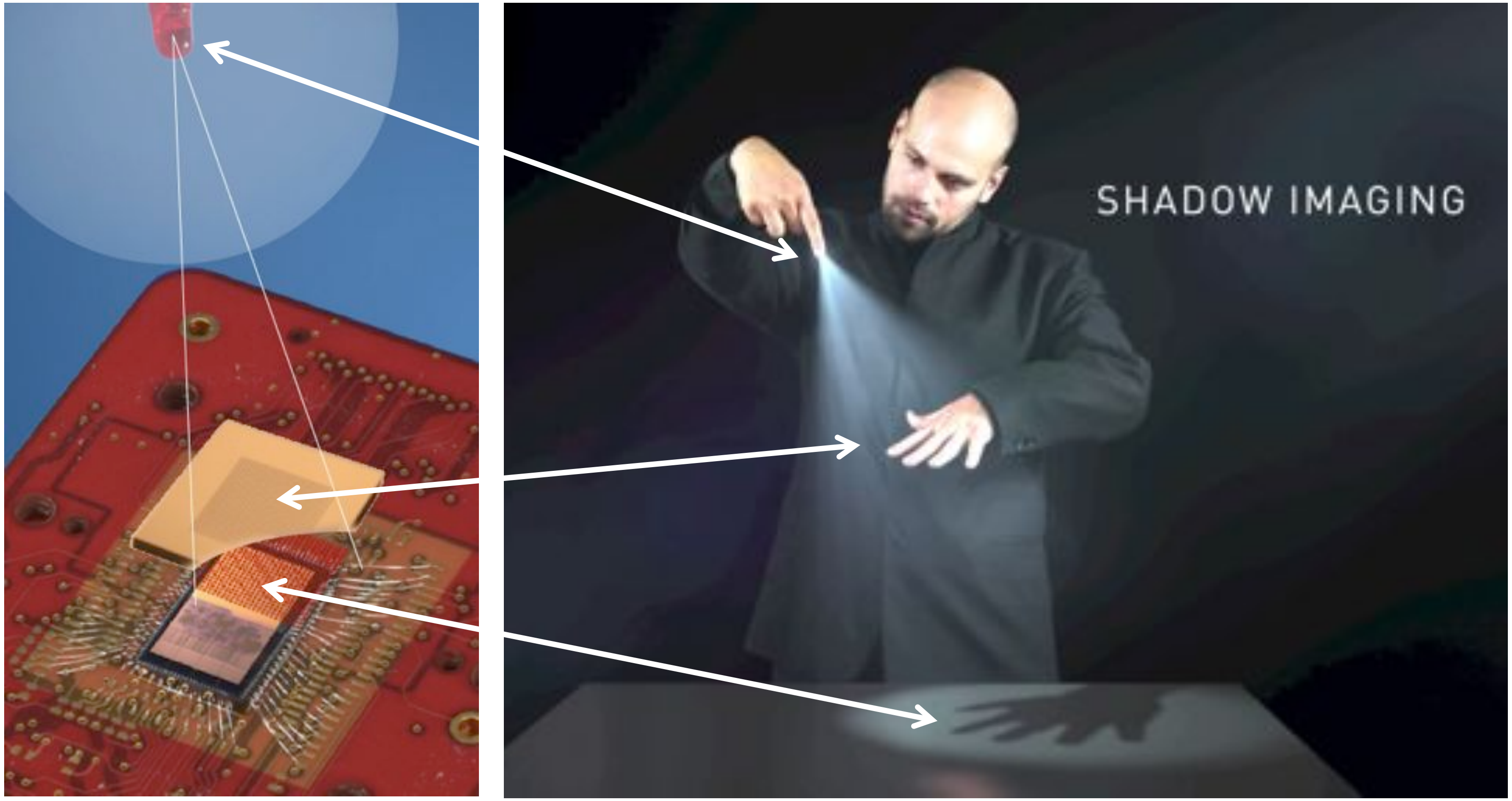
Sizes … from 1 Å to the infinite



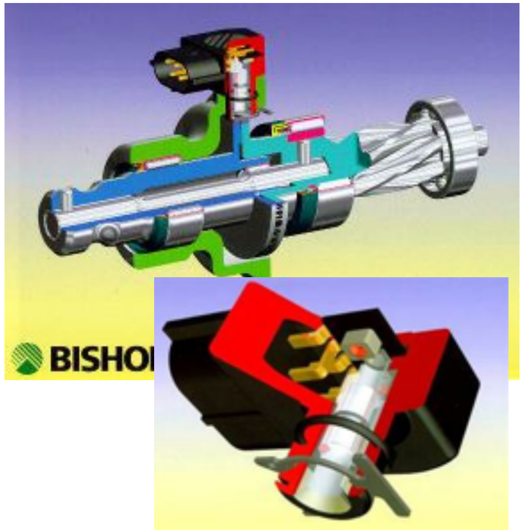
Limits of the SpaceCoder technology

Dynamics and precision at the same time

spaceCoder principle – Shadow Imaging

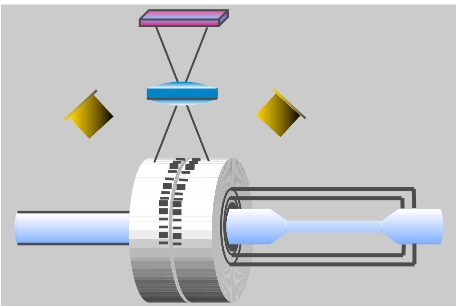


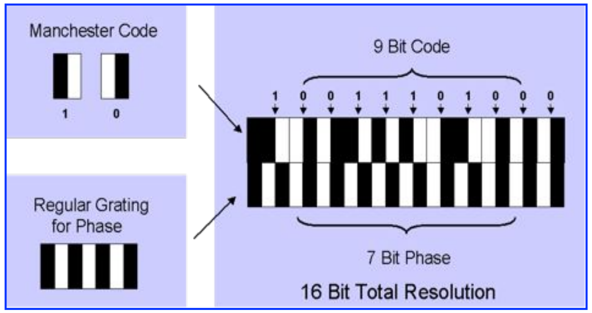
Optical torque sensor for EPAS applications

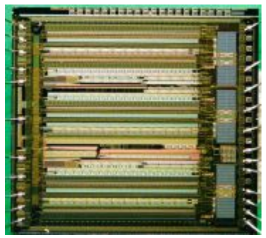


Measure torque, absolute angle and angular rate

- 4 clock cycles for all computing
- Torque precision: 0.05 Nm
- Angle resolution: 18 bits
- Environmental: -40 to 125 °C
- Tangent pre-distorted flash ADC (patented)
- Robust Sensor with phase extraction (patented)
- Power consumption: 5 mA

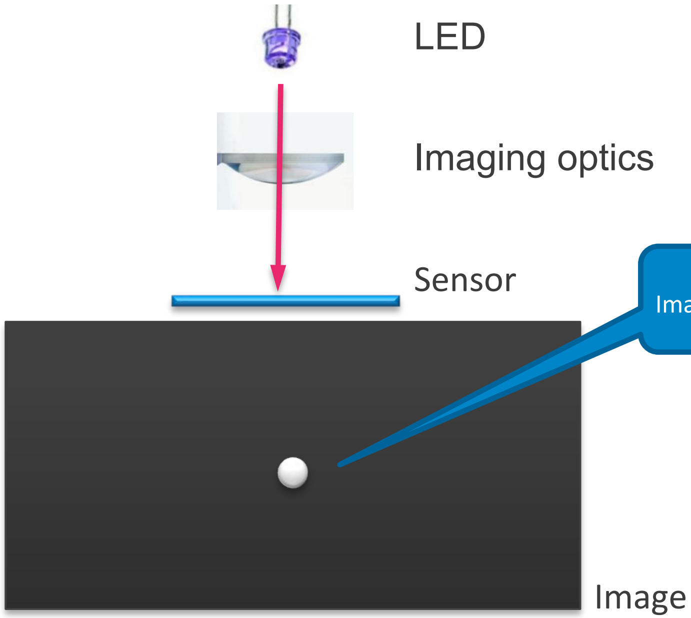






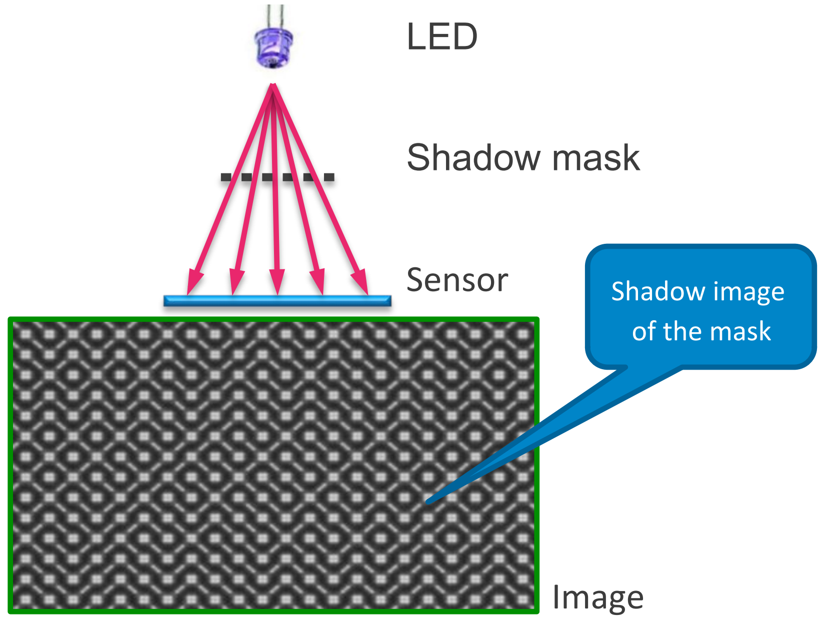
SpaceCoder

Calculating X-Y position of the LED



Center of gravity of the light spot. The information is LOCAL, carried only by few pixels

Limited precision accuracy in the order of the pixel size (5 µm)

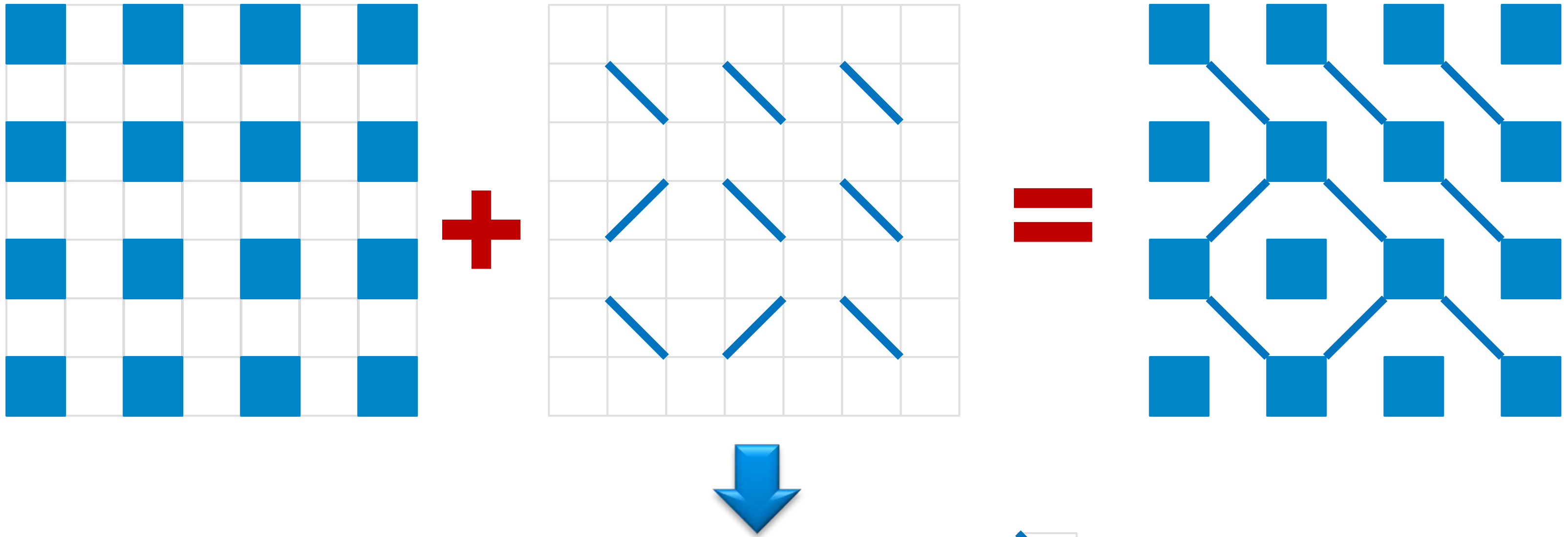


High precision phase measurement of periodic signal. The information is distributed into entire image ALL pixels carries LED position info

Very HIGH precision & accuracy 1'000 times sub-pixel (0.005 µm) is reached

Pattern for 2D absolute position measurement

regular grating	binary code	combined code
for **high-precision**, **relative** measurement	for **low-precision**, **absolute** measurement	for **high-precision**, **absolute** measurement



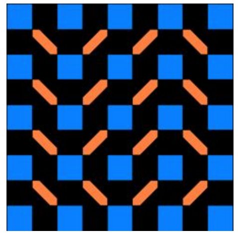
0	0	0
1	0	0
0	1	0

Pascal Heim, Edo Franzi, Péter Masa
Système de positionnement 2D à mesure de phase en quadrature
CSEM RAPPORT D'INVENTION No. 06/37

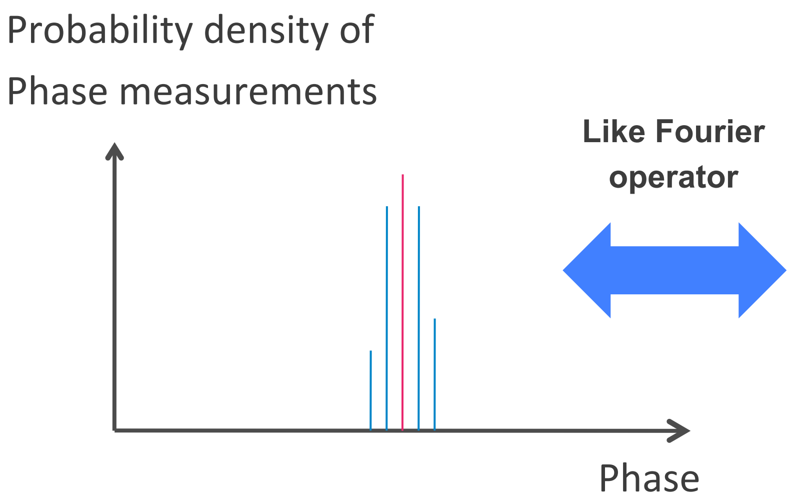
Absolute nanometric measurement system

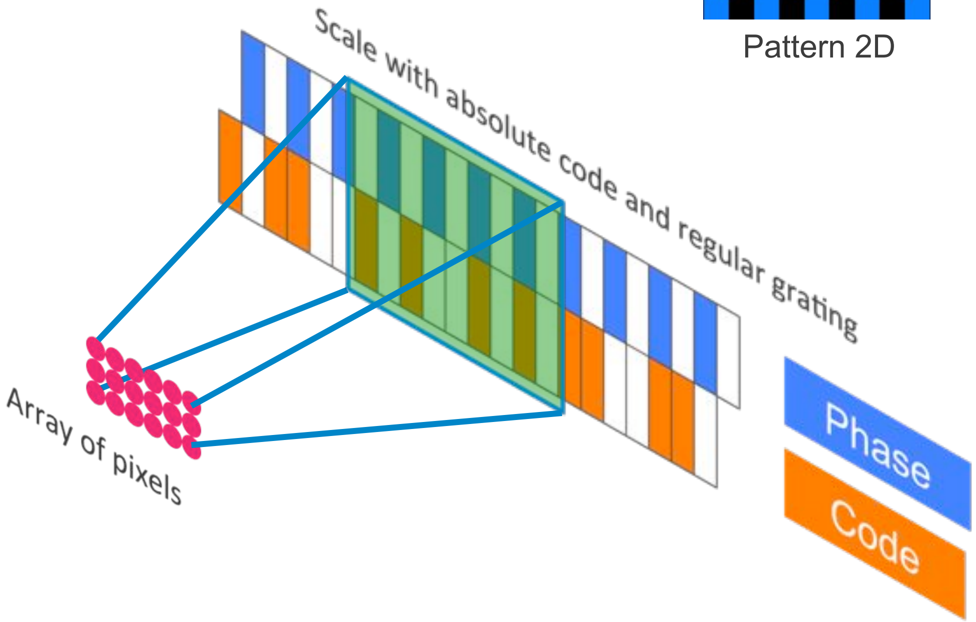
How to measure large absolute distances with nanometric resolution?

- 2 types of markings; an absolute code and a regular grating
- The absolute code provides the MSB of the measurement
- The phase of the regular grating gives the LSB
- Each pixel acts as a single sensor
- We take advantage from the statistics



Pattern 2D

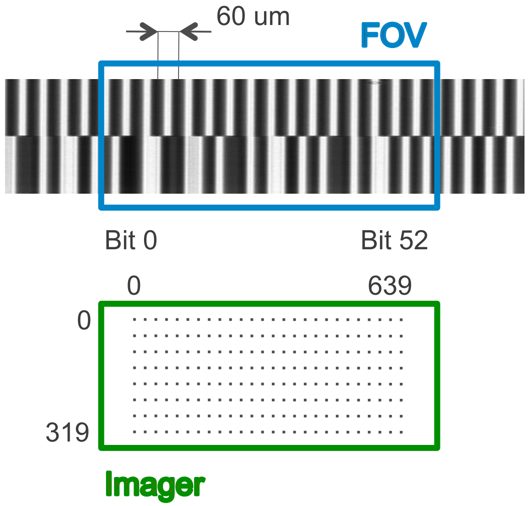




Absolute nanometric measurement system

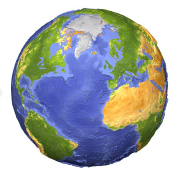
The limits of the measurement principle: an example:

- Low cost, 60 µm period, chromium-plated scale
- Low cost, low resolution VGA imager (640 x 320 pixels) having 5 µm pixels fixes 60 / 5 = 12 pixels / period
- This allows to represent an absolute code of 640 / 12 = 53 bits; and to interpolate with a factor 60’000 (16 bits) for resolving 1 nm
- 53 + 16 bits represent 1 nm precision over ~ 590’000’000 km!

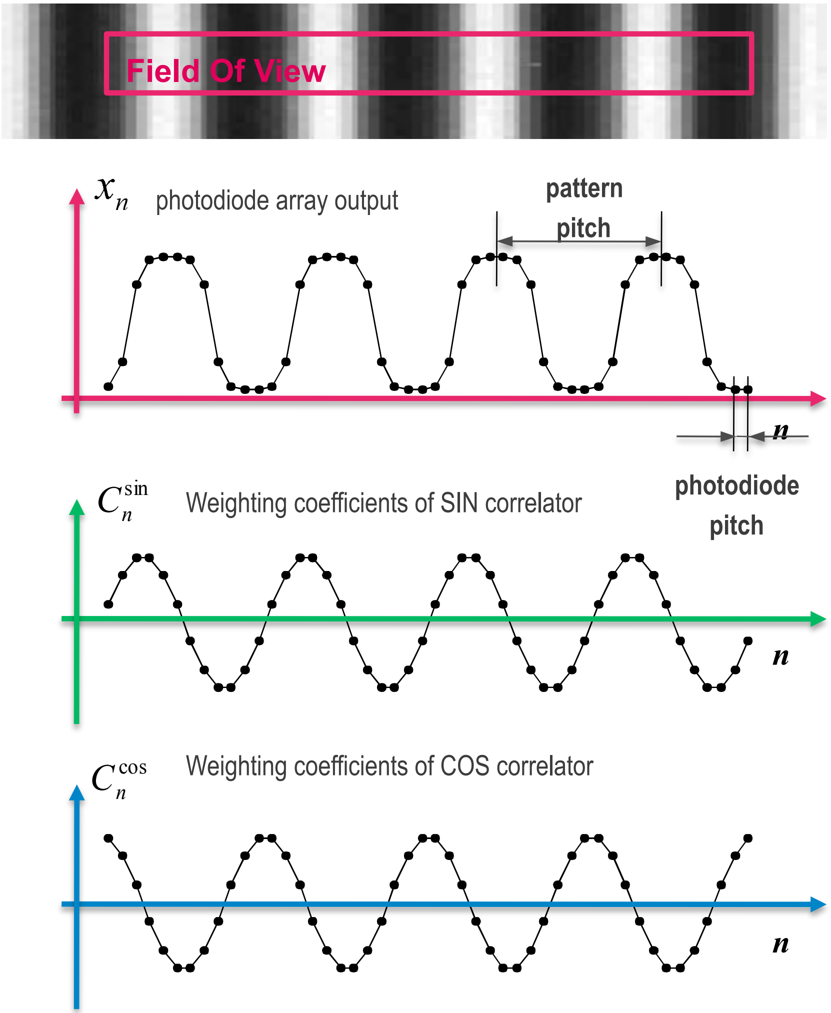


150’000’000 km

1 nm



Fine position measurement, vector decomposition



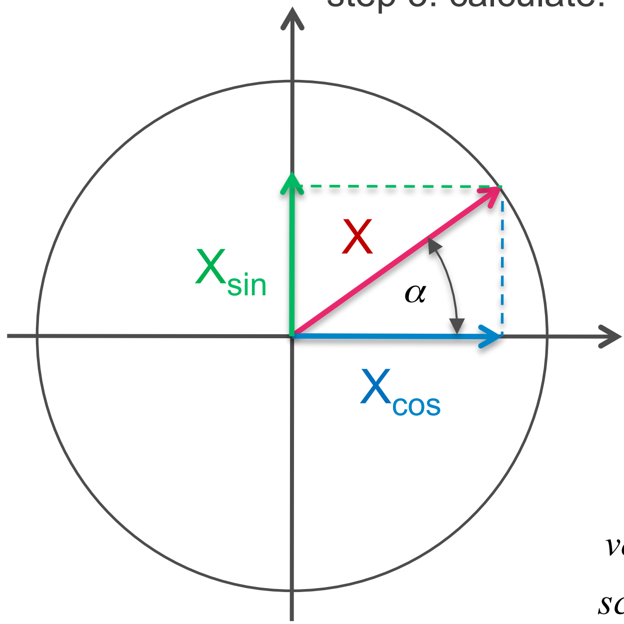
Given X = X_n, a periodic pattern, an n-element vector of photodiode outputs α is the phase or position of X

3 Steps to calculate α:

step 1: calculate: $X_{sin} = \sum_n X_n C_n^{sin}$

step 2: calculate: $X_{cos} = \sum_n X_n C_n^{cos}$

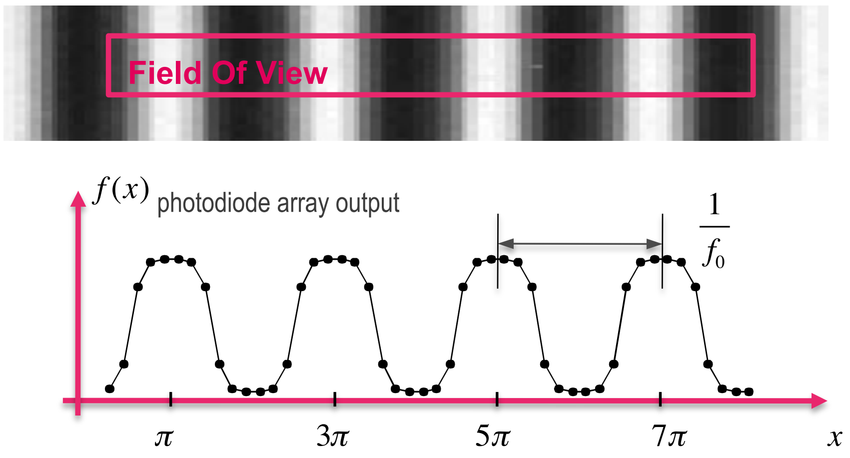
step 3: calculate: $\alpha = \arctan\left(\frac{X_{sin}}{X_{cos}}\right)$

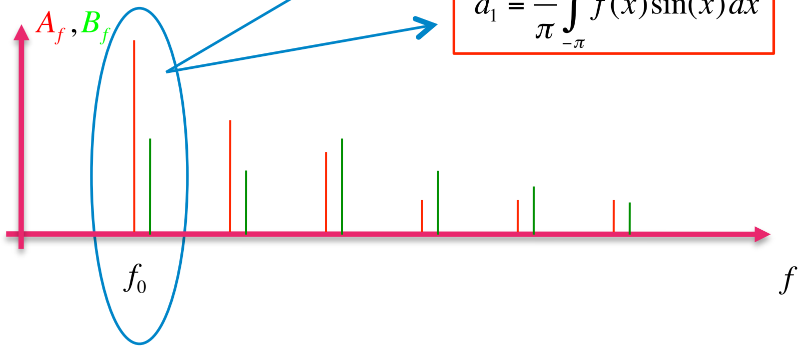


$vectors: \; X, X_n, C_n^{sin}, C_n^{cos}$

$scalars: \; X_{sin}, X_{cos}, \alpha$

Insensitive to marking quality





$$b_1 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos(x)\,dx$$

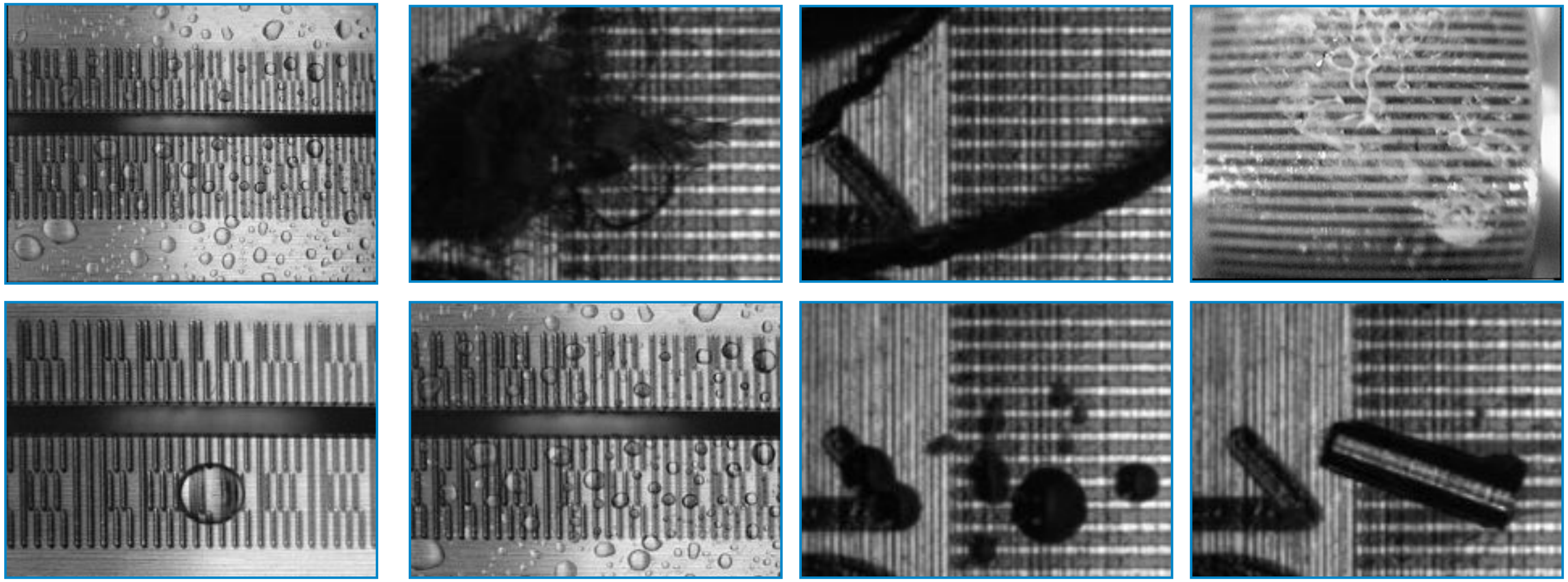
$$a_1 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\sin(x)\,dx$$

$$f(x) = a_0 + \sum_{n=1}^{\infty}\left[a_n\cos(nx) + b_n\sin(nx)\right]$$

Where is the information ?

- The information is the phase of the fundamental frequency …
- … which is distributed in the entire image (all pixels contain information about it!)
- The phase is largely insensitive to the printing quality of the marking (a_1 and b_1 affected only by the spatial regularity of the marking)
- Large redundancy; the method tolerates large degradations of the marking

Robust principle

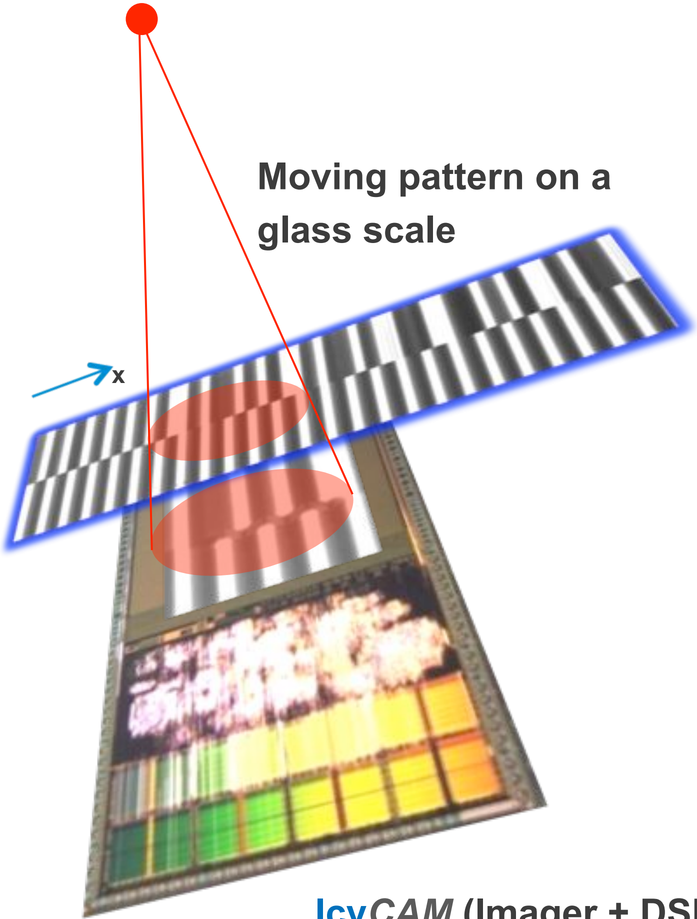


Extensive analysis and verification proves the robustness of the concept for automotive

- **Phase information is distributed in the entire FOV**

  part of the pattern can be corrupted or occluded

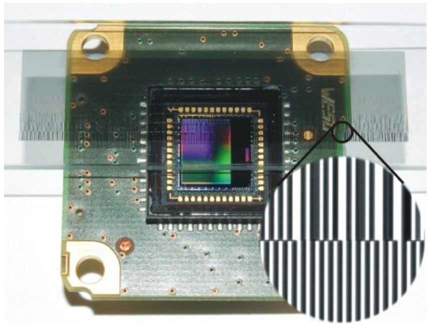
Shadow imaging: absolute 1 DOF measurement



IcyCAM (Imager + DSP)

Main benefits

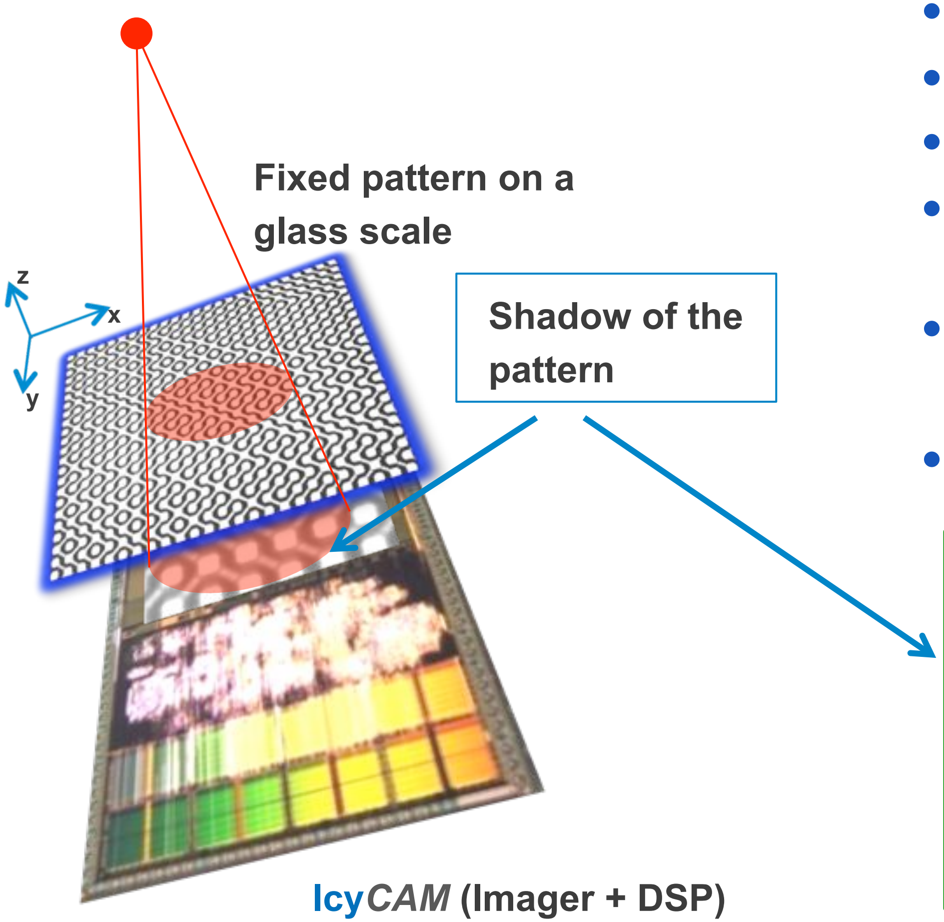
- No lenses
- Contact-less 1 DOF optical measurement
- True absolute position
- Suitable for linear or circular encoders
- Precision better than 1 nm
- Practically infinite dynamics
- No drift nor calibration
- Many implementations possible (camera, ASIC, DSP, FPGA) from quick solution to peak performance combined with low cost



SpaceCoder

Shadow imaging: absolute 6 DOF measurement

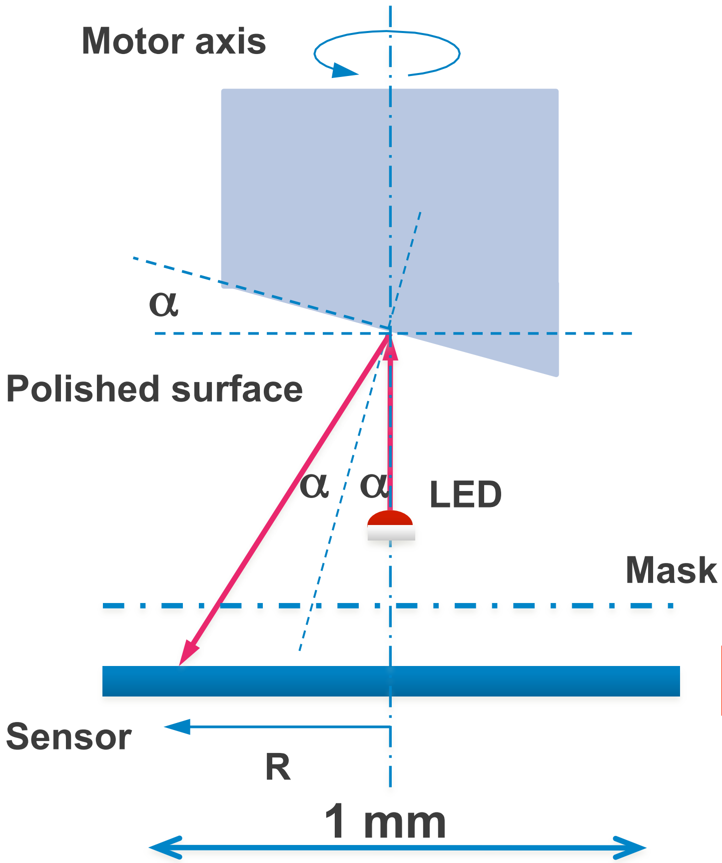
Moving light source $p = f(x,y,z,\alpha_x,\beta_y,\gamma_z)$



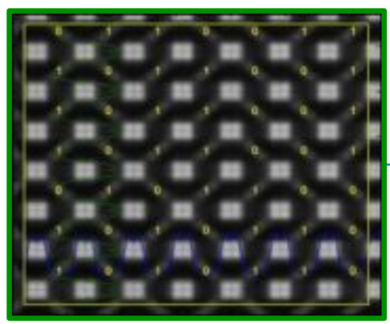
Main benefits

- No lenses
- Absolute position of the light source
- Small volume (size of a sugar cube)
- Multi-axes $x,y,z,\alpha_x,\beta_y,\gamma_z$ 6 degrees of freedom measurements
- Precision close to 10 nm (x,y)
  and 100 nm (z)
- No drift nor calibration

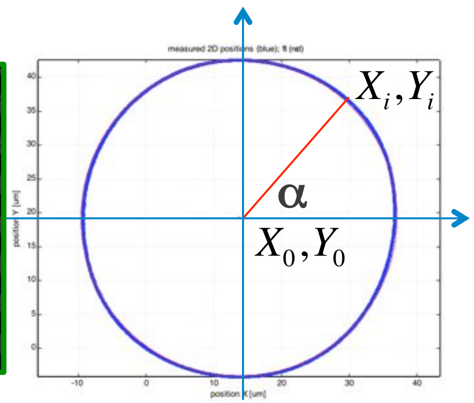
Rotary encoders:



- No need for an encoder disk
- Insensitive to the assembly tolerances
- Small size and volume
- No inertia (for end-of-shaft arrangements)
- No drift
- One shot calibration to determine X_0, Y_0



Shadow image



$$\alpha = arctg \frac{Y_i - Y_0}{X_i - X_0}$$

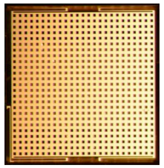
SpaceCoder

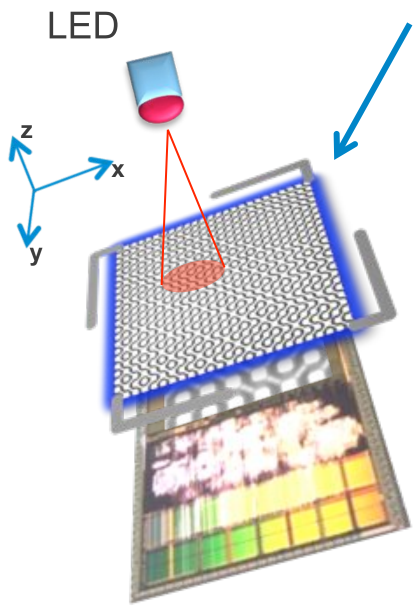
Absolute 6 DOF MEMS sensor

Accelerometer mass

Pressure MEMS

$$p = f(x, y, z, \alpha_x, \beta_y, \gamma_z)$$





Cortex – m4 (MEMS / Grating + Imager + DSP)

Main benefits

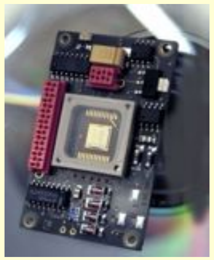
- No lenses
- Small volume (size of a sugar cube)
- Multi-axes $x, y, z, \alpha_x, \beta_y, \gamma_z$ absolute 6 degrees of freedom measurements
- Precision close to 10 nm in all the axes
- On chip signal processing
- Digital output of …
  - Acceleration,
  - Speed,
  - Pressure,
  - Deformation,
  - 6 DOF absolute position,
  - Other processed information,

… via SPI or other µC bus

Various platforms proposed

Full-custom ASIC

High-speed
Harsh environment
Low-Power
Fixed configuration

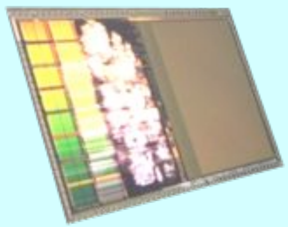


Generic ASIC + DSP

Optical front-end

DSP

High-speed
Harsh environment
Flexible
Scalable
Space compatible



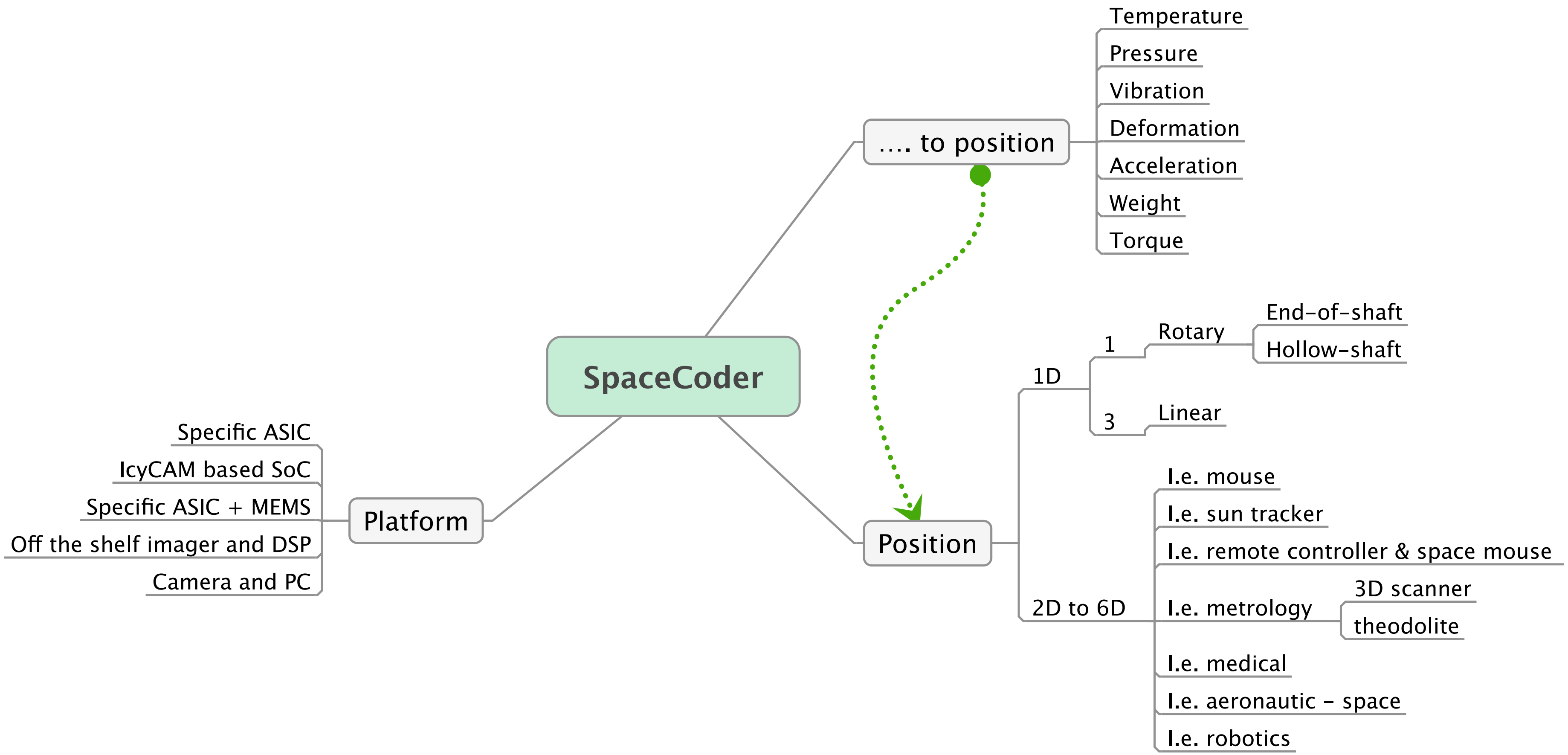
Imager + DSP

Imager

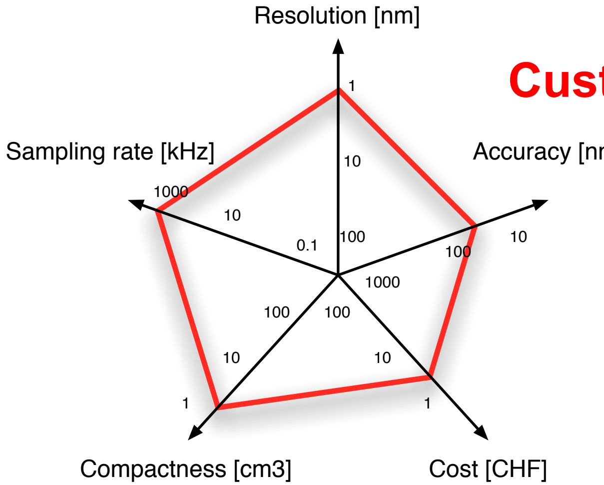
DSP

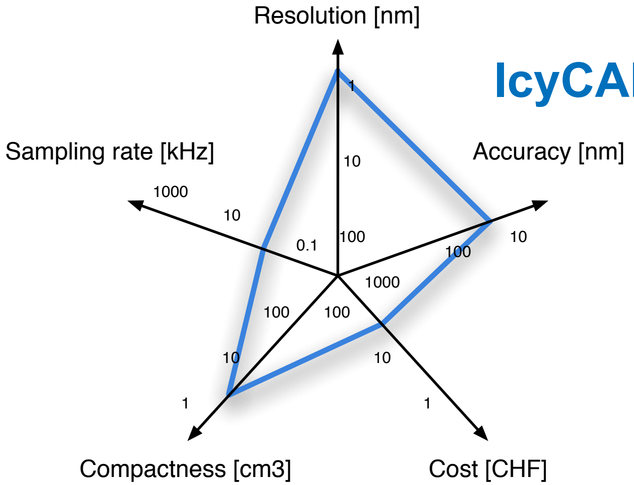
Flexible
Scalable
Space compatible

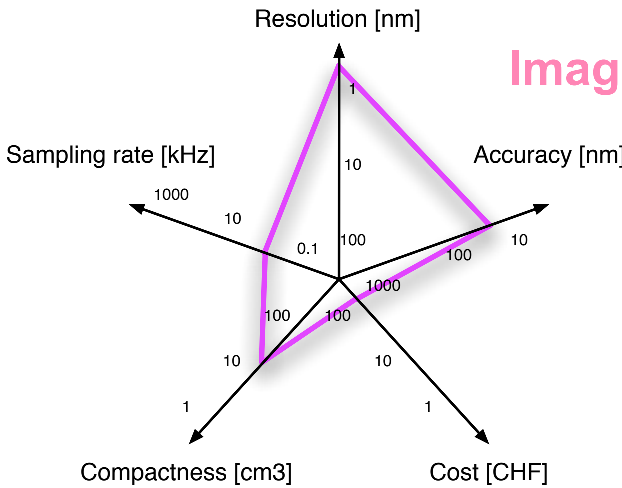
SpaceCoder as a sensor

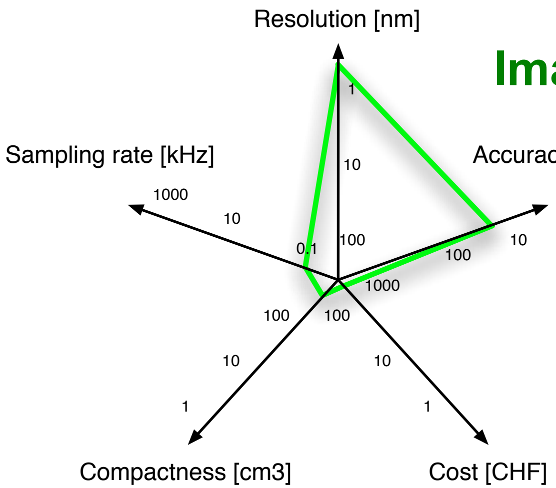


SpaceCoder as a sensor

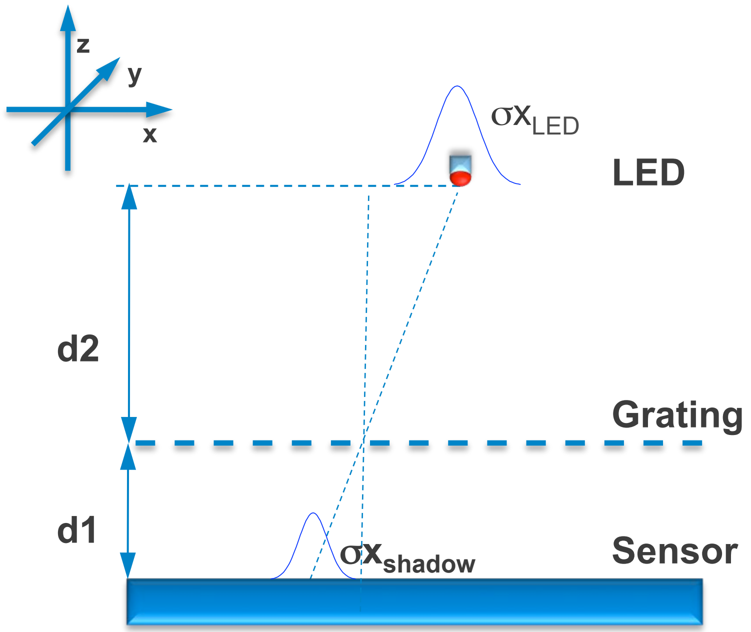








X,Y precision, accuracy



Noise of the shadow position measurement:

σx_{shadow}

From shadow to LED position:

$$\sigma x_{LED} = \sigma x_{shadow} \frac{d_2}{d_1} = 0.005um \cdot \frac{100mm}{1mm} = 0.5um$$

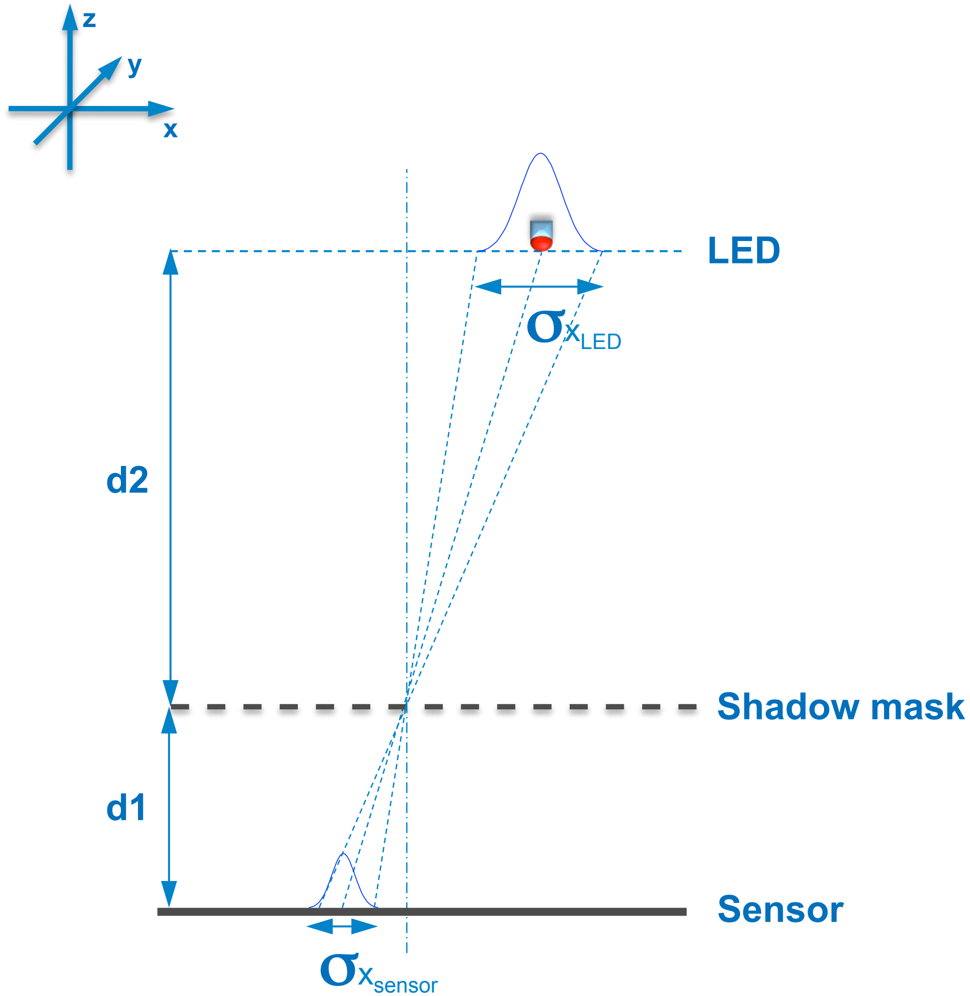
Precision σx_{shadow} affected by:

- Mainly by shot noise, image contrast, photon flux: ~0.1 to 5 nm
- Grating pitch (proportional)
- Noise of: ADC, dark current, read-out, kTC, etc: 0.1 to 5 nm
- Achievable precision: ~0.25 nm

Accuracy σx_{shadow} affected by:

- Accuracy of the grating (thermal, mechanical stability, etc)
- Frequency mismatch: ~100 to 5’000 nm
- Contamination: ~ 100 to 5’000 nm
- Grating pitch (proportional)
- Refraction with certain gratings
- Overall mechanical and thermal stability of the system excluding the sensor: ~? nm
- Achievable Accuracy w/o calibration: ~100 to 1’000 nm
- Achievable Accuracy with calibration: ~10 to 1’000 nm

Sensor-Level precision VS 3D precision (X,Y)



Example: LED (X,Y) precision at 1m

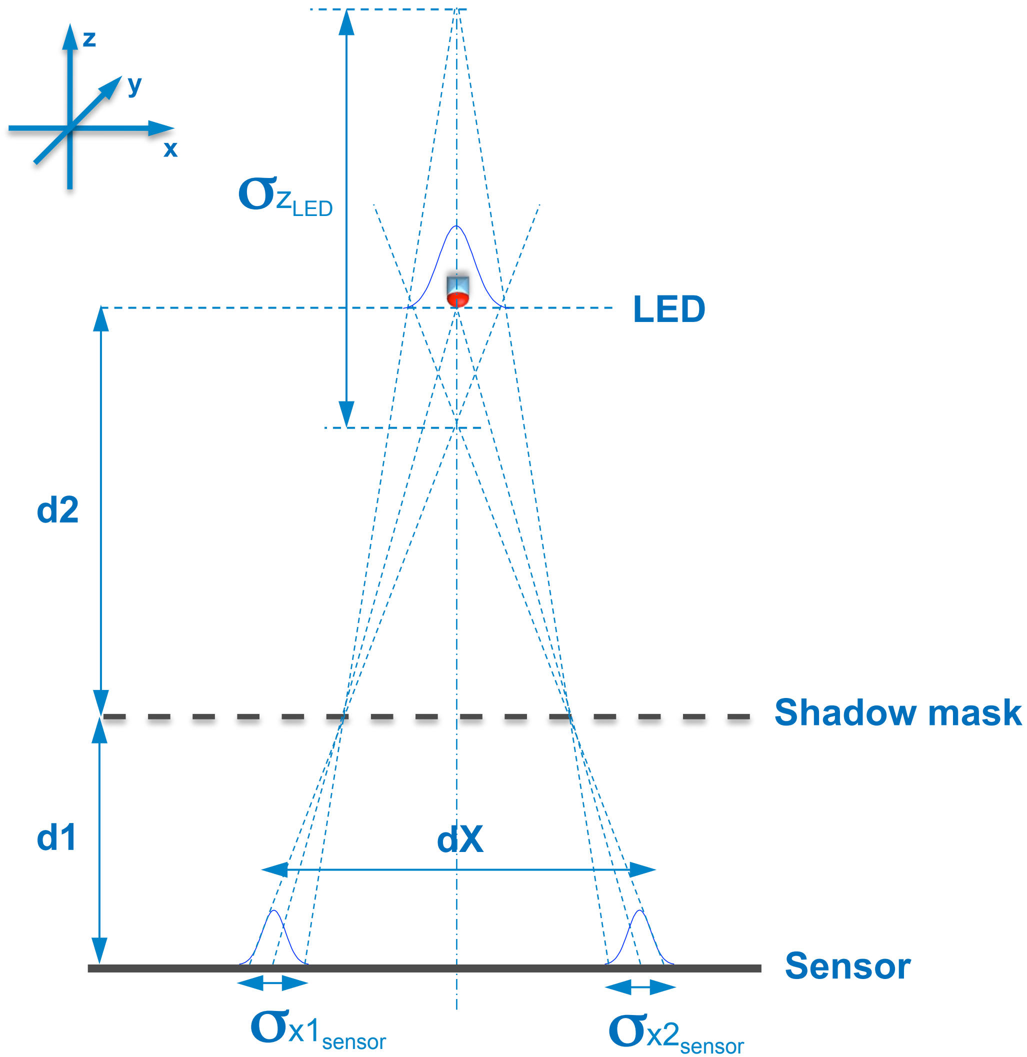
σx_{sensor} # 5 nm

d2 # 1 m

d1 # 2 mm

$$\sigma x_{LED} = \frac{d2}{d1} \sigma x_{sensor} = 2.5\ \mu m$$

Sensor-Level precision VS 3D precision (Z)



Example: LED (Z) precision at 20 cm

σx_{sensor} # 5 nm

d1 # 2 mm

Aptina sensor

dX # 1.4 mm ⇨ σz_{LED} # 140 μm

E2V sensor

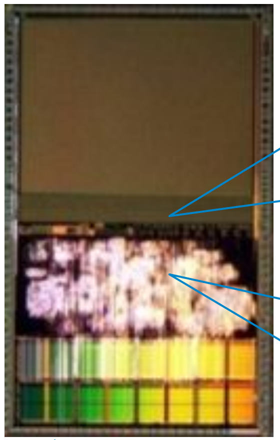
dX # 2.6 mm ⇨ σz_{LED} # 70 μm

2 sensors

dX # 10 cm ⇨ σz_{LED} # 4 μm

Icy*CAM* : a single chip measuring system

Image



$$b_1 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\cos(x)\,dx$$

$$a_1 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x)\sin(x)\,dx$$

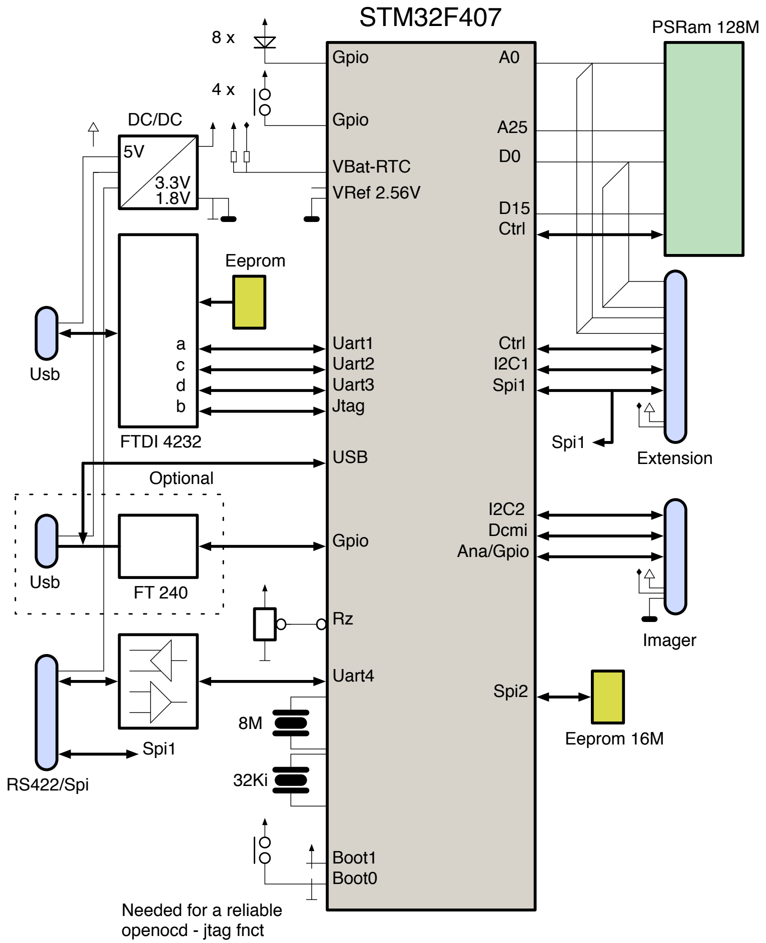
$$\alpha = \arctan\frac{b_1}{a_1}$$

Absolute position:

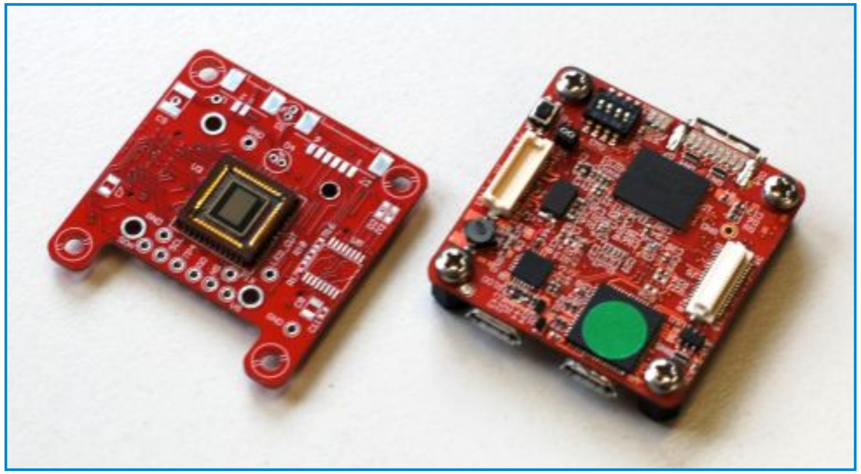
$$x, y, z, \alpha_x, \beta_y, \gamma_z$$

- Technology: 0.18 µm
- Front-end: 320 x 240 pixels (QVGA)
- Luminance: **digital log representation**
- Contrast: **magnitude and orientation (M e$^{j\Theta}$)**
- Dynamic range: 130 dB
- DSP: 50 MHz DSP icyflex
- Memory: 128 Kbyte on chip SRAM
- I/Os: UART, SPI, PPI, SDRAM, ..
- Programmable: GNU tool suite (gcc, gdb, gas)
- Suitable for medium speed (~ 1 kHz) high precision 1 DOF, 2 DOF or 6 DOF measurement systems

ARM® Cortex™-M4 vision & metrology platform



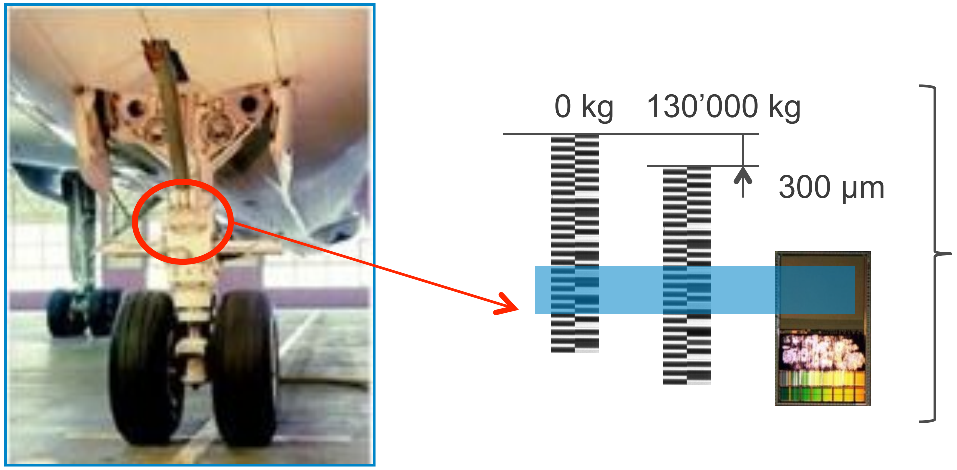
- ARM® Cortex™-M4 DSP instructions
- 200 MIPS @ 160MHz, 40µW/MHz
- Example: absolute encoder:
  - 1D or 2D linear : resolution X,Y: 5 nm
  - Rotary: resolution: 0.5 urad, 0.1 arcsec
  - 3D mouse or remote controller
  - Sampling rate: 300 Hz (up to 3 KHz)
- Industrial interfaces(SPI, PPI, UART, GPIO, etc.)
- Dimensions (35 x 35 mm)



csem

Application: A380 weight balance

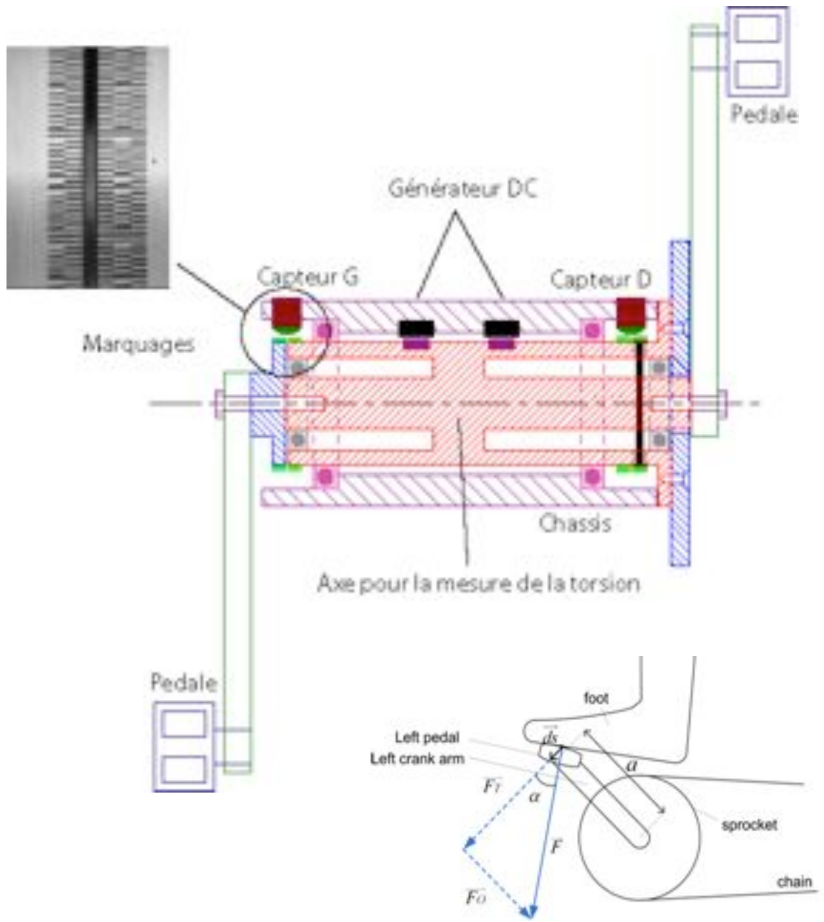
- Balance of the airplane weight for reducing the fuel consumption
- Measurement of airplane weight with 1 kg of precision
- The max. weight is ~ 520’000 kg distributed on 4 points
- We have to measure 1 kg to 130’000 kg resolution (18 bits)



The load causes a deformation and a displacement of a marking

$$1kg \rightarrow \frac{300x10^{-6}}{130x10^{3}} = 2.3nm$$

Cycling performance monitoring and analyzer



Characteristics

- Accurately measures torque on both pedals as a function of exact pedal position and pedal speed. Monitors cycling technique and performance with the utmost precision.
- Low cost sensor designed for direct integration in the standard parts such as the bottom bracket.
- Battery-less operation, can be directly powered during the pedal movement.
- Simple system: encoder ASIC, LED, a marked cylinder, torsion bar. The last 2 are integral part of the bottom bracket.
- Different configurations are possible: i.e. the system could also be integrated in the pedals or in the crankset.

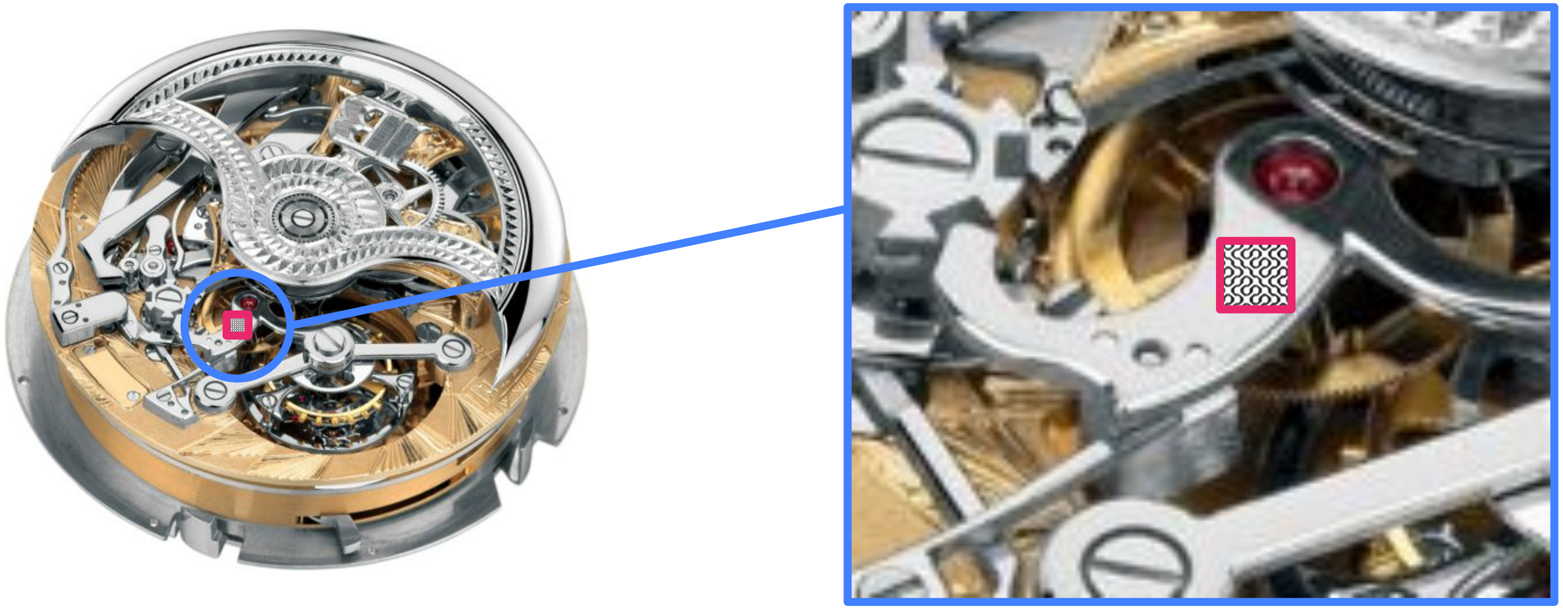
Dictionary

Bottom bracket

Crankset

pedal

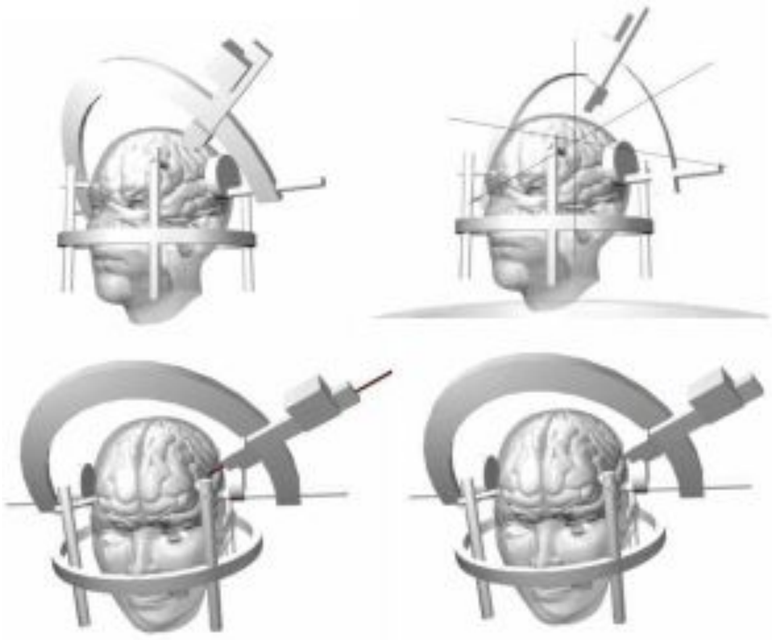
µMouvement analysis

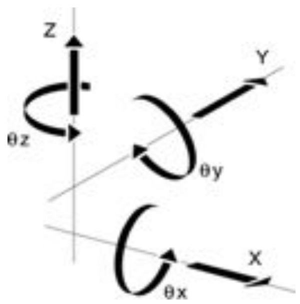


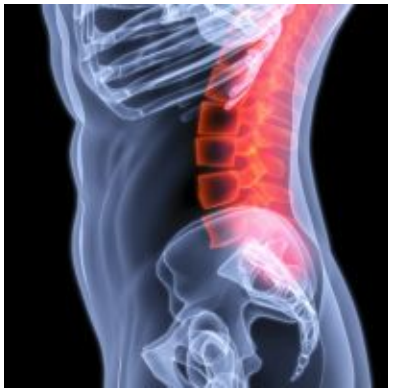
Main benefits

- No inertia, passive observation
- Multi-axes analysis
- Precise characterization of mobile elements

Precise positioning of surgical tools





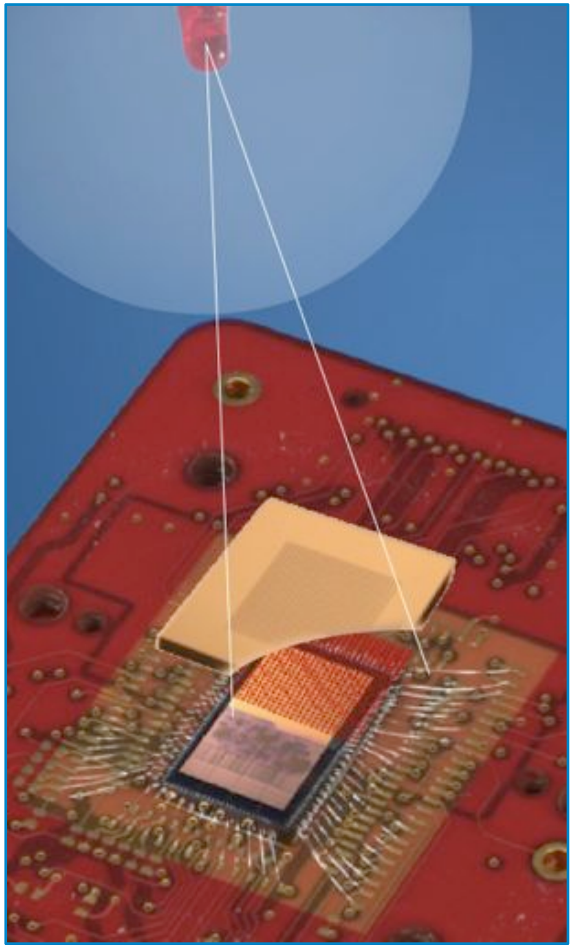


Characteristics

- Micrometer precision 3D-6D positioning of surgical tools
- For computer-assisted, robotic surgery, precise, controlled actions
- For manual surgery tools can move freely in space, no wires are needed
- High-precision, e.g. spine or brain surgery, minimally-invasive, with minimal risk
- Improves patient safety
- Precise, controlled actions reduce or eliminate the tissue trauma traditionally associated with open surgery
- Sterilization proof
- Real-time
- Miniature sensor, implant compatible, biocompatible

6 DOF pointing device

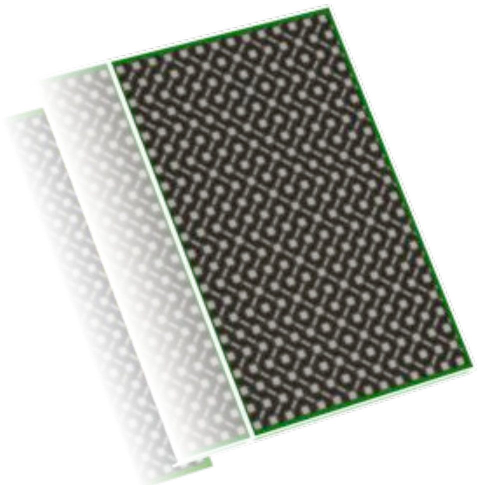
Conclusions …



… absolute, nanometric measurement systems

- Perfect matching between vision and microelectronic techniques
- Original approach (patented) using a special pattern
- Extremely high precision and dynamic measurement systems
- Insensitive to pattern marking and tolerant to contamination
- Small dimensions (size of a sugar cube)
- Many configurations possible (1 DOF, 2 DOF, 3 DOF, 6 DOF, linear, rotary)
- Low cost and compact

Thank you for your attention.



For more information please contact:

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