NEREID

NanoElectronics Roadmap for Europe: Identification and Dissemination

Advisory Board Meeting

Sardinia, June 16, 2018

WP4 Functional diversification
Task 4.1 Smart Sensors

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HORIZON 2020

Introduction

The main objective of T4.1 Smart Sensors are:

- To define the foundation of a European roadmap for low power smart sensors, as enablers of new applications, services and markets in **Internet-of-Things** serving in **European priorities such as automotive, airborne and healthcare industries**.

- To define the content in terms of **priorities and metrics** for various categories of **mature and emerging key families of sensors**, with a special attention to energy needs for wearable sensors.

3. Selection of Technologies and Experts (I)

❖ Technological experts for the 1st Domain Workshop:

- **Cosmin Roman** (ETH Zürich, CH) *Energy-efficient sensors based on carbon*
- **Denis Flandre** (UCL, BE): *SOI CMOS devices and sensors*
- **Frans Widdershoven** (NXP semiconductors, NL) *CMOS Capacitive Sensor*
- **Maaike Taklo** (SINTEF, NO) *IR and MEMS sensors*
- **Mireille Mouis** (GINP, FR) *Nanonet-based FET devices for label-free sensing*
- **Teodor Gotszalk** (University of Wroclaw, PL) *MEMS and NEMS sensors*
- **Walter De Raedt** (IMEC, BE) *Wearable and IoT sensors enabling health*
- **Florin Udrea** (former Cambridge CMOS, UK) *Smart gas sensors*"

3. Selection of Technologies and Experts (II)

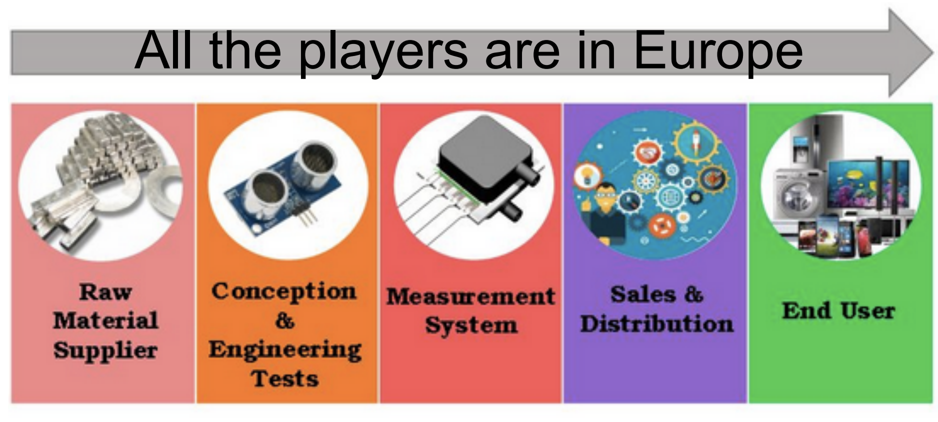
- Technological Experts cross-domain workshop (Barcelona, Dec. 2017)
  - **Saverio Da Vito** (ENEA, Italy) *Mobile air quality monitoring*
  - **Javier Del Campo** (CNM, Spain): *Health smart sensors*
  - **Carles Cané** (CNM, Spain) *Environmental monitoring*

- Other Experts consulted throught the writing of the roadmap
  - **Maaike Ob de Beeck** (IMEC, BE): Implantable medical sensors
  - **Christian Silber** (Robert Bosch GmbH, GE): Automotive electronics
  - **Luis Fonseca** (CSIC, ES): MEMS sensors and integration
  - **Johannes Classen** (Robert Bosch GmbH, GE): 3D MEMS
  - **Hoël Guerin** (Xsension, CH): Physiological signal monitoring
  - **Laurent Dugoujon** (STMicroelectronics, FR): Automotive Image Devices
  - **Holger Schmidt** (Infineon Technologies AG, Ge): Automotive Systems

Smart sensor roadmapping in NEREID

❖ Choices for sensor roadmapping in NEREID:

- Automotive
- Healthcare



Rationale:

- Significant for European industries
- Existing leadership
- Potential high growth in 21st century
- High innovation potential and creation of economic value: JOBs!
- Relevant for **Internet of Things** revolution
  - Trillion of sensor planet
  - Zero-power smart systems
  - Key enabling technologies
- **Future Health**: Internet-of-Humans

for personalized and preventive healthcare

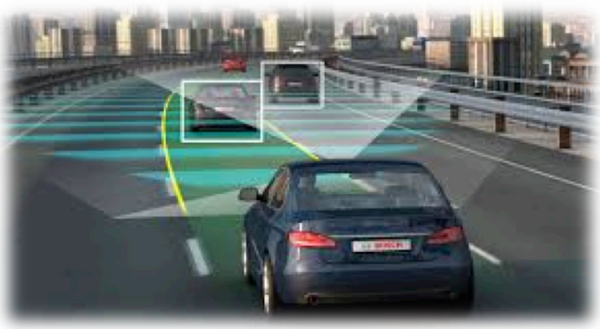
- **WHAT ABOUT SUSTAINABILITY?**

4 BEuros spent every day by EU on intervention-based health care
20% of Europeans will be over 65 by 2025
75% of the health cost are due to human behavior
3% only of the health budget is spent on prevention

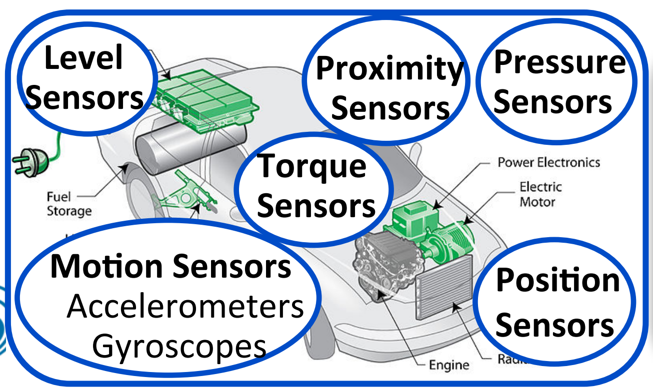
Automotive in NEREID

Existing EPoSS roadmap and ERTRAC EU policies with defined milestones

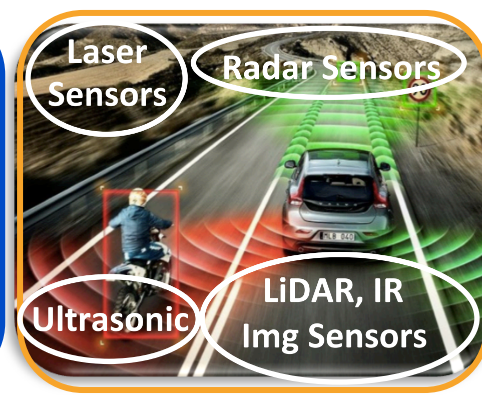
- Less energy consumption (fuel-efficient and hybrid EVs)
- Less pollution (reduction of carbon footprint)
- Improved safety and security



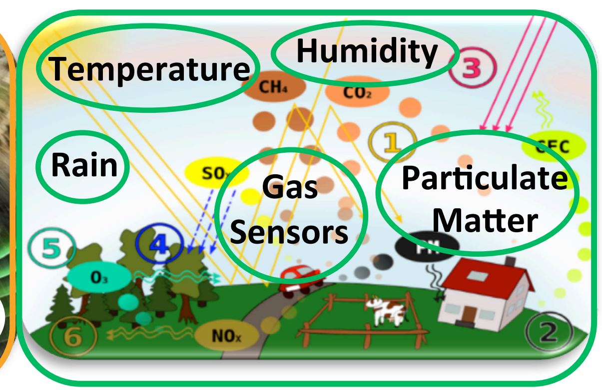
Automotive performance sensors: Inertial and motional sensors



Advanced Driver Assistance System: ADAS



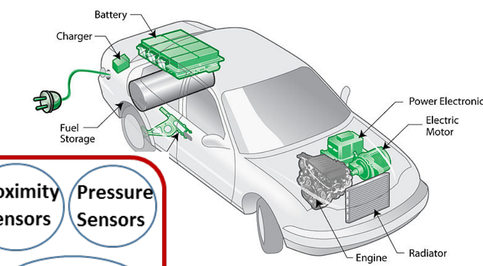
Environmental monitoring : Pollution & Climate status



Automotive Technology Requirements

- **High quality standards** and requirements (high resolution and contrast of the cameras)
- **Safety/ Security** big data storage & computing power (filter, process)
- **Stability** in harsh environment (large T° range)
- **Long life-time,** failsafe and have redundancy
- **Low power**
- **Low cost**
- **Transferable** to all vehicucle types
- **Miniaturization** of all the functions (sensors…)

Concept 1: *Sensors for navigation and car's basic system performance*



Level Sensors · Torque Sensors · Proximity Sensors · Pressure Sensors

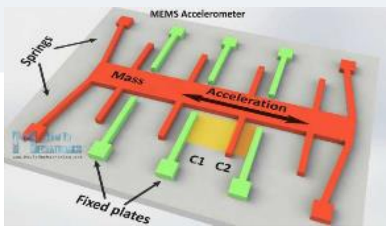
Motion Sensors: Gyroscopes, Accelerometers

Position Sensors: Linear, Angular

Improve Accuracy !

Shared manufacture infrastructure costs with other applications !

Functions\ Sensors	Motion *$5 billion by 2022*	Pressure	Optical position	Displacement	Proximity
Airbag deployment	X	X	X		
Parking assistance			X	X	X



Other functions:

Automotive
Dead reckoning
Anti-theft
Pre-sage system
Black box
Infotainment
Medical (for implantable devices)

Automotive
Tire Pressure Monitoring System
Electronic Engine Control
Side Crash detection
Pedestrian impact detection
Seat Comfort System
Idle stop
Fuel Vapor
Barometric Air Pressure (BAP)
Medical
Blood pressure measurement
Bladder examination
Tactile sensors for fall detection
Mass balance (to detect nanoparticles/atoms)

Car industry uses on average 20 MEMS per car

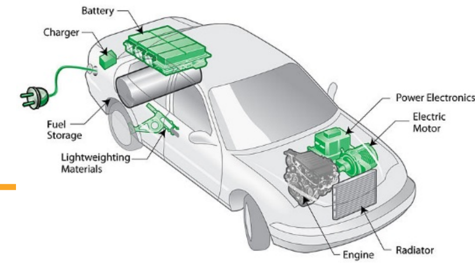
R&D: research and development → DP: Demonstration and Prototype → RS: Regulations and Standards → Market Introduction

1) Motion Sensors	Medium term: 5+	Long term: 10+
Potential for application or Application needs and Impact for Europe		
Roll over detection for airbag	XXX	XXX
Dead reckoning	XX	XXX
Anti-theft	X	XX
Pre-sage system	XX	XX
Black box	X	XXX
Infotainment	XX	XX

2) Pressure Sensors	Medium term: 5+	Long term: 10+
Potential for application or Application needs and Impact for Europe		
Automotive		
Tire Pressure Monitoring System	XXX	XXX
Air Bag deployment	XX	XXX
Electronic Engine Control	XX	XX
Side Crash detection	R&D and DP	Market Introduction
Pedestrian impact detection	DP and RS	Market Introduction
Seat Comfort System	R&D	Market Introduction
Idle stop	XX	XX
Fuel Vapor	XX	XX
Barometric Air Pressure (BAP)	XXX	XX
Medical		
Blood pressure measurement	XXX	XX
Bladder examination	XXX	XXX
Tactile sensors for fall detection	XX	XXX
Mass balance (to detect nanoparticles/atoms)	X	XX

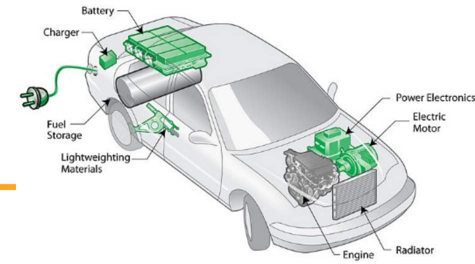
Note; R&D: research and development, DP: Demonstration and Prototype, RS: Regulations and Standards

Concept 1: *Sensors for navigation and car's basic system performance*



Motion Sensors	Medium term: 5+	Long term: 10+
Key research questions or issues for Motion Sensors		
Accelerometers	TRL 9	TRL 9
Gyroscopes	TRL 9	TRL 9
Figures of Merit		
Acceleration	+/- 2 g range	
Form factor	Important feature for bionic applications	
Power consumption	< 1 mW	
Price	< 1 $	
Output data range	1 kHz	
Resolution	>8 bit	>10 bit
Lifetime	10 years	20 years
Packaging	Customized packaging	Standard packaging

Concept 1: *Sensors for navigation and car's basic system performance*

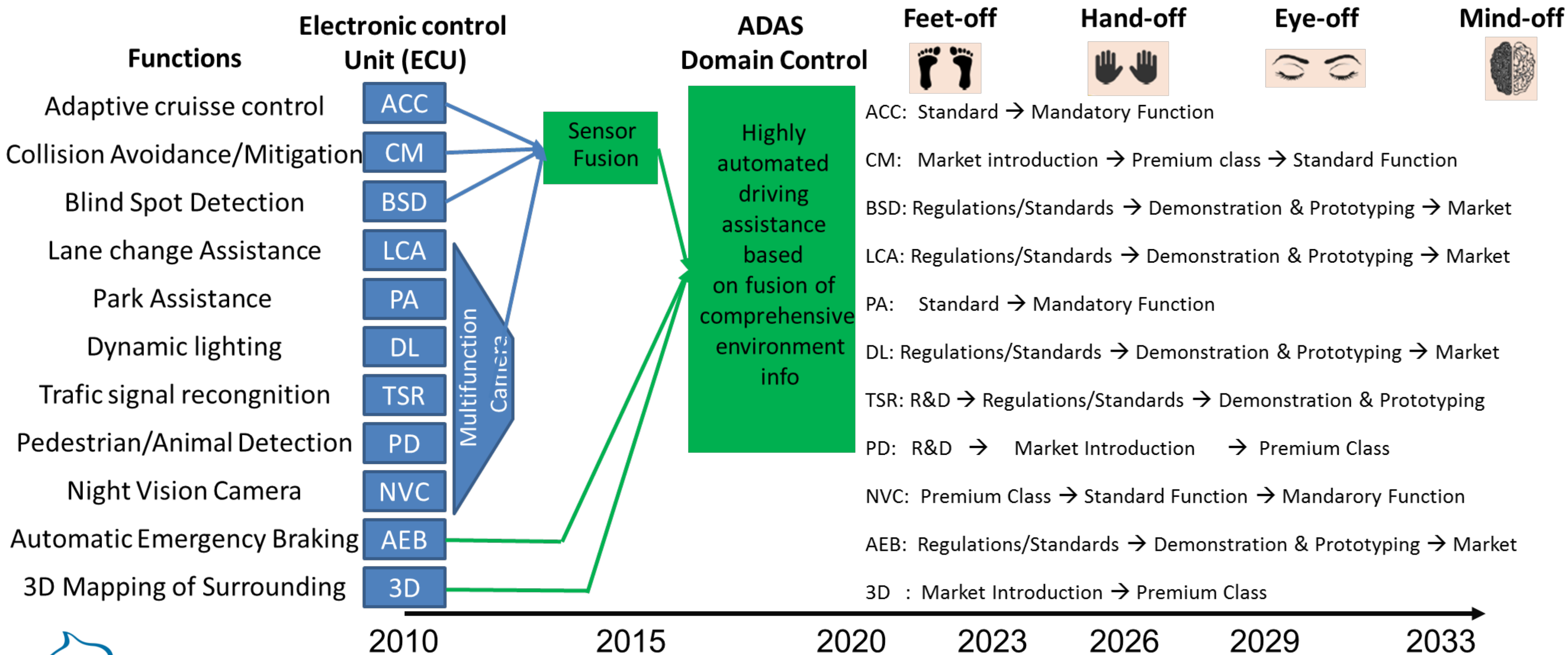


Pressure Sensors	Medium term: 5+	Long term: 10+
Technology and design challenges		
Piezoresistive	TRL 7-8	TRL 9
Capacitive (MEMS)	TRL 9	TRL 9
Optical (Fiber optic)	TRL 9	TRL 9
Electromagnetic	TRL 9	TRL 9
Resonant Solid state	TRL 7-8	
Figures of Merit		
Pressure level precision/ relative accuracy	0.005 hPa	0.001 hPa
Temperature accuracy	0.5 °C	0.1 °C
Pressure temperature accuracy	0.5 Pa/K	0.1 Pa/K
Measurement time	3 ms	< ms
Power consumption (average/Standby current)	1 mA	< 100 nA
Supply voltage	1.2 – 3.6 V	< 1 V
Package dimension	<1 mm^3	XXX
Robustness (-20, 200°C), Lifetime, Stability, cycing	10^{10}	10^{12}

Concept 2: Advanced Driver Assistance System: ADAS

- **Mandatory functions:** safety reasons
- **Standard functions:** effortless
- **Differentiation functions:** new driving experience

Premium class car
→ Comfort class



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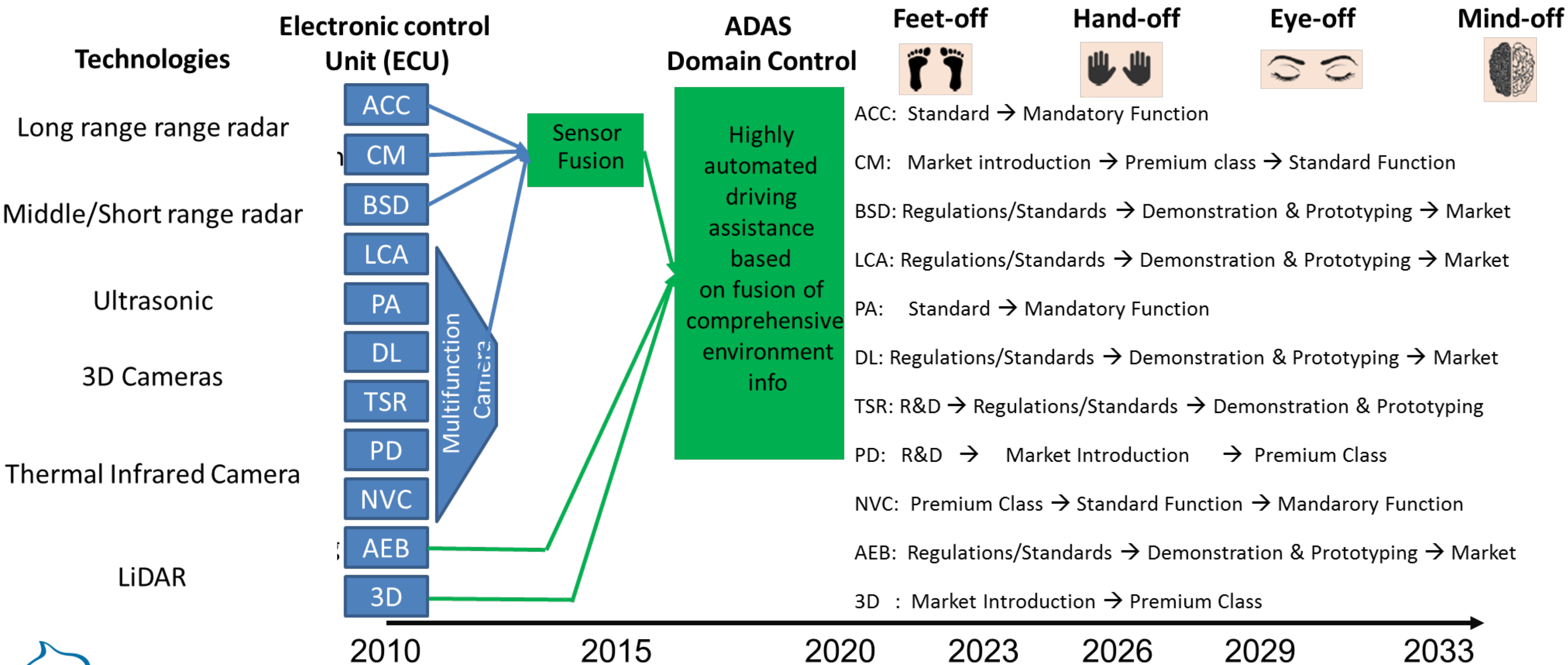
Premium class car → Comfort class

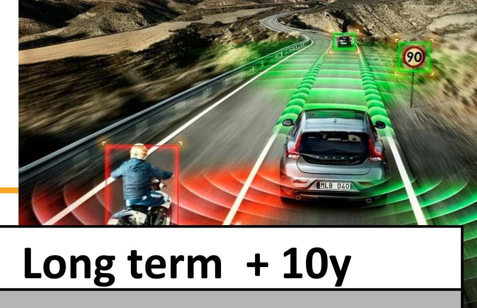


Advanced Drive Assistance Systems (ADAS): sensors for autonomous cars

Key research questions or issues	Medium term + 5y	Long term + 10y
Long/medium-short range Radars	XXX (LRR)	XXX (LRR)
(3D) Image Sensors	-Improve sensitivity, with smaller pixel size -Flicker-free & HDR -In-cabin NearIR Global Shutter	- New sensing layer to replace Silicon - Local computer vision - Global shutter/flicker-free/HDR -Secure data links
LiDAR - Light Detection and Ranging	Increase resolution Price of laser	Integration into a small module
Thermal infrared Sensors – Night vision Camera	Resolution increase	- Cost - Data fusion with CMOS imaging sensor
Spectrometers	XX	XXX

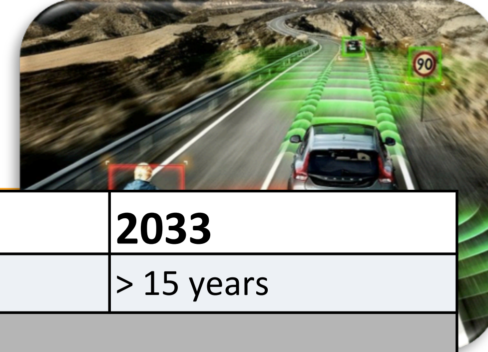
Note; XXX: Critical, high priority or more probably to come first, XX: Less critical, middle priority or less probable to come first, X: no critical, lower priority or unprovable to achieve it in this time-period.

Advanced Drive Assistance Systems (ADAS): sensors for autonomous cars



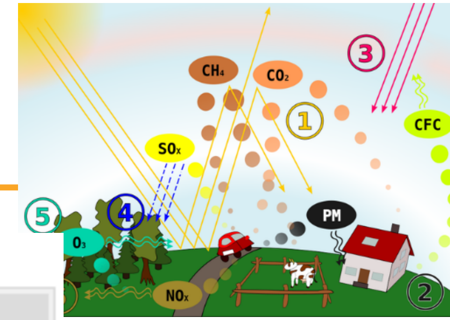
Technology and design challenges	Medium term + 5y	Long term + 10y
Short/Long range Radars		
Silicon	XX	XXX
Silicon Germanium	XXX	XXX
(3D) Image Sensors		
Charge-coupled device (CCD)	Fully replaced by CMOS	Fully replaced by CMOS
Complementary metal - oxide semiconductor (CMOS)	XXX	XXX
Single-phonon avalanche diode (SPAD)	- Higher integration with 3D stacking - Pixel size decrease	Both Time-of-Flight & Image within the same SPAD sensor
3D hybrid stack backside illumination (BSI)	Market Introduction	Standard Function
LiDAR Component		
Laser scanner	XX	XXX
Position and navigation systems (GPS/GNSS)	XX	XX
3D cameras (as before)	XXX	XXX
Photodetectors (solid-state as Si avalanche photodiode)	XX	XXX
MEMS	XXX	XXX
Thermal Infrared Sensors – Night vision camera		
Pyroelectric	XX	XX
Thermopiles	XX	XX
Microbolometers	XXX	XXX

Concept 2: Advanced Driver Assistance System: ADAS



Figures of Merit	2023	2026	2029	2033
Reliability – Lifetime - Failsafe	10 years	12 years	14 years	> 15 years
Short/Long range Radar (24-77 GHz/ 79-81 GHz)				
Distance of object recognition	0.2-30m /250 m			
Price	30 $/ 100 $	25 $/ 80 $	20 $/ 60 $	10 $ /50 $
N° of sensors/car	4/ 1	5/1	5 / 2	6/ 2
(3D) Image Sensors				
Price	5$ to 10 $	5$ to 10 $	5$ to 10 $	5$ to 10 $
N° of sensors/car	5	6	8	10
Detection Range (m)	1-100 m	1- 150 m	1- 200 m	1-250 m
Field of view	60 °	90 °	120 °	180 °
Pixel size/Number	3.5 um/ 2 Mp to 8 Mp	3 um/ 2 Mp to 10Mp	2.5 um/ 3 to 12 Mp	2 um/ 4 to 16Mp
Thermal Infrared Sensors – Night vision Camera				
Price	< 500 $	< 400 $	< 300 $	< 250 $
N° of sensors/car	1	1	2	3
Detection Range (NIR/LWIR)	150/ 400 m	160 / 425 m	180/475 m	200/ 500 m
LiDAR				
Price	< 250 $	< 200 $	< 150 $	< 100 $
N° of sensors/car	1	1	2	2 to 4
Detection Range / accuracy	1-100 m / < 2 cm	1-150 m / < 1 cm	1-200 m / < 0.5 cm	1-250 m /< 0.1 cm
Scanning angle/ accuracy	270 ° /5-10 °	300 ° /4-8 °	330 ° /3-7 °	360° / 2-5°
Scanning time	20 Hz	50 Hz	75 Hz	100 Hz

Concept 3: *Pollution/Air quality monitoring based on gas sensors*



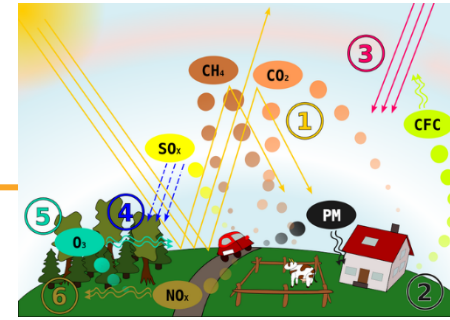
Common air quality index calculation grid

Index Class	Grid	ROADSIDE INDEX						BACKGROUND INDEX							
		Mandatory pollutant			Auxiliary pollutant			Mandatory pollutant				Auxiliary pollutant			
		NO2	PM10 1 hour	PM10 24 hours	PM2.5 1 hour	PM2.5 24 hours	CO	NO2	PM10 1 hour	PM10 24 hours	O3	PM2.5 1 hour	PM2.5 24 hours	CO	SO2
Very High	>100	>400	>180	>100	>110	>60	>20000	>400	>180	>100	>240	>110	>60	>20000	>500
High	100	400	180	100	110	60	20000	400	180	100	240	110	60	20000	500
	75	200	90	50	55	30	10000	200	90	50	180	55	30	10000	350
Medium	75	200	90	50	55	30	10000	200	90	50	180	55	30	10000	350
	50	100	50	30	30	20	7500	100	50	30	120	30	20	7500	100
Low	50	100	50	30	30	20	7500	100	50	30	120	30	20	7500	100
	25	50	25	15	15	10	5000	50	25	15	60	15	10	5000	50
Very Low	25	50	25	15	15	10	5000	50	25	15	60	15	10	5000	50
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

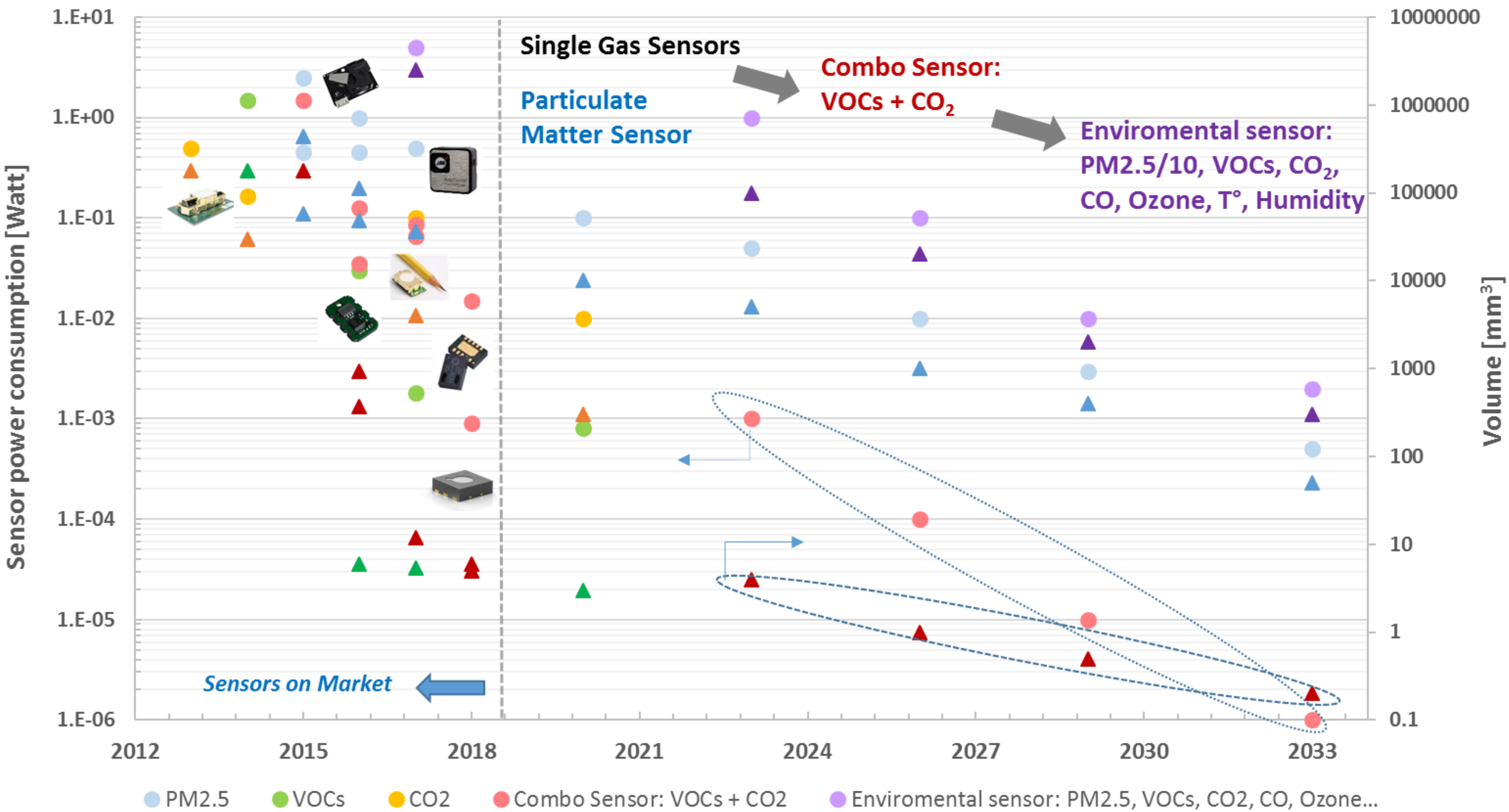
- NO2, O3, SO2: hourly value / maximum hourly value in µg/m3
- PM10, PM2.5: hourly value / maximum hourly value or adjusted daily average in µg/m3
- CO: 8 hours moving average / maximum 8 hours moving average in µg/m3

http://www.airqualitynow.eu

Concept 3: *Pollution/Air quality monitoring based on gas sensors*



- **Gas Sensor: NO_2, O_3 , CO, SO_2**
- **Particulate Matter Detection: PM2.5 and PM 10**



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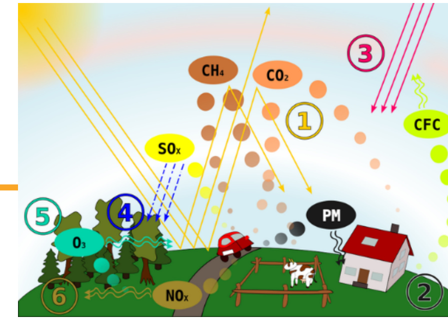
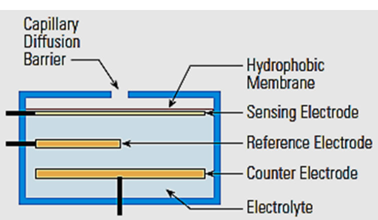
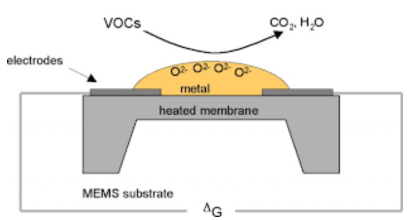


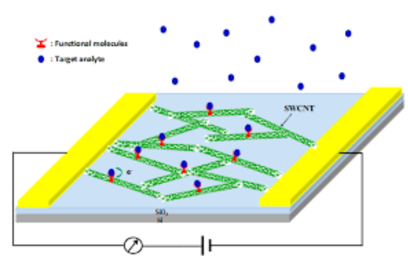
Technology and design challenges (TRL)	Medium term + 5y	+ 15y
Electrochemical Sensors	TRL 9	TRL 9
Optical IR sensors (non-dispersive IR: pulsed emitter and detectors) – No portable	TRL 9	TRL 9
Solid-state CMOS Capacitive imagers	TRL 4-5	TRL 8-9
Metal Oxide sensors (MOX)	TRL 9	TRL 9
Nanometal oxides – Resistive MOX-CMOS miniaturization	TRL 5	TRL 7-8
MEMS Micro-hotplates MOS	TRL 8-9	TRL 9
Other MEMS based sensors: miniaturized IR, resonating layers, GasFET, Chromatography	TRL 3	TRL 6
Laser scatter detection	TRL 8-9	TRL 9
Carbon-based (SW-CNTs)	TRL 3-4	TRL 7-8
Quantum dots, nanotubes and nanowires	TRL 2-3	??
Polymer sensing layers	TRL 1-2	??

TRL: tecnhology readiness level

9	Commercialized
8	Pre-production
7	Field Test
6	Prototype
5	Bench / Lab Testing
4	Detailed Design
3	Preliminary Design
2	Conceptual Design
1	Basic Concept







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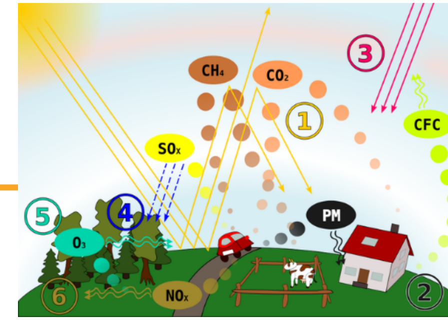
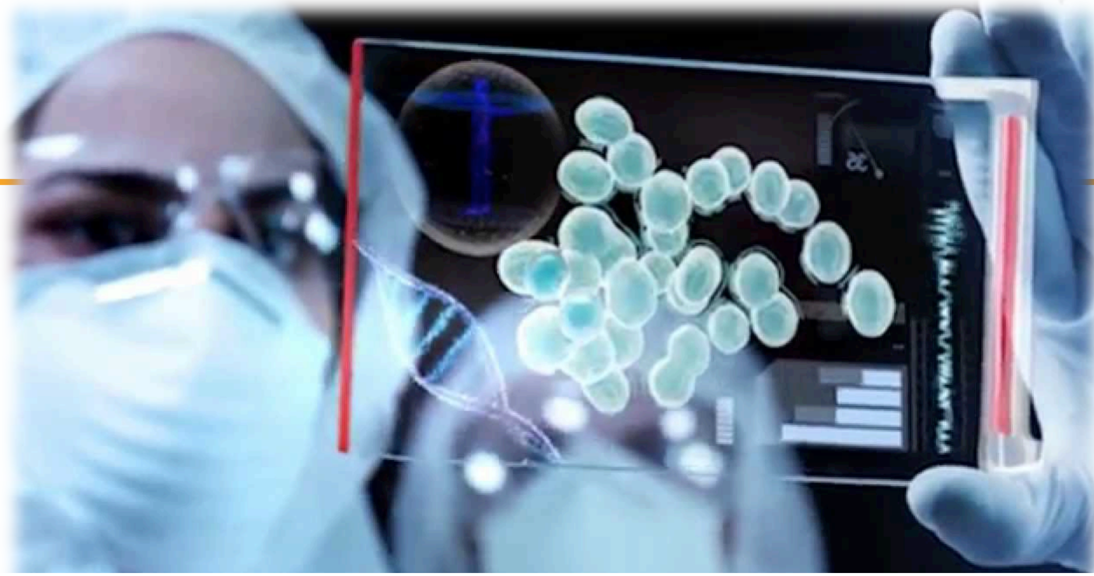
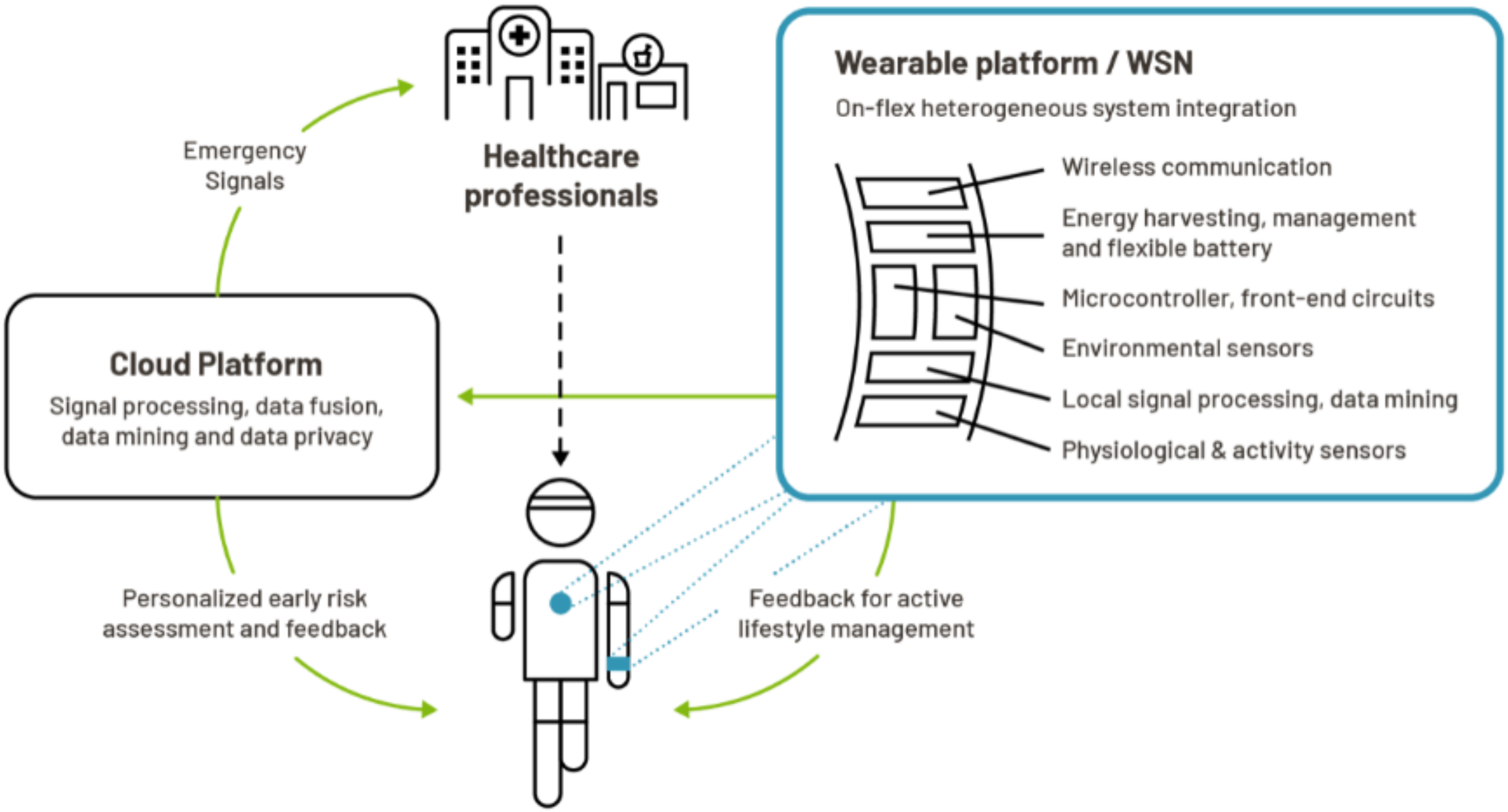


Figures of Merit	Medium term + 5y	Long term + 15y
Gas sensors Technical Requirements		
Sensitivity (high ppb, medium/low ppm)	< 100 ppm	< 10 ppm
Response Time	<0.1 s	ms
Sensor element power consumption	< 200 nW	<50 nW
Energy consumption (including the read-out circuitry)	< 100 mW	< 10 mWatt
Particulate PM 2.5 Technical requirements		
Sensitivity (high ppb, medium/low ppm)	50 mg/m^3	1 mg/m^3
Response Time	5 min	1 min
Sensor element power consumption	< 100 mWatt	< 10 mW
Resolution (Effective number of bits ENOB, N)	1	2
Other requirements		
Reliability - Lifetime	5 years	10 years
Package Size (for mobile application)	< 3 cm^2	< 1 cm^2
Business Requirements		
Price	2 $	< 1$
Volume (low, medium, high)	High	high
Market (emerging, niche, growing, mature)	Emerging	Growing

Healthcare in NEREID

- Future smart health
- Internet of Things healthcare
- A new ecosystem





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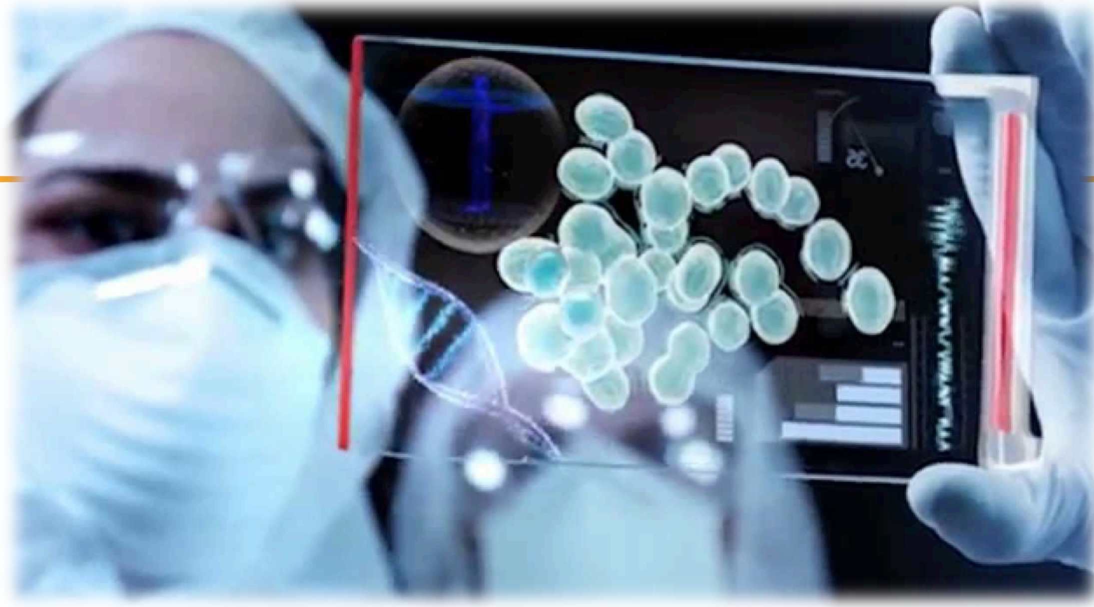


Applications

- Drug Development
- Patient Monitoring
- Clinical Operation
- Clinical Imaging
- Fitness & Wellness

End Users

- Patients
- Biotech companies
- Research labs of pharma
- Healthcare providers & players
- Government authority

Devices

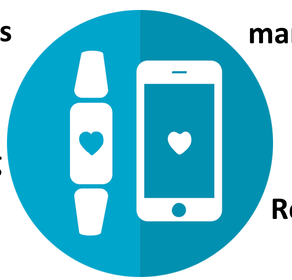
mHealth - Wearable Sensors

Monitoring & Diagnostic:

Vital signals

Neuro-monitoring

Fetal, Obstetric



Therapeutic:

Pain management

Glucose

Respiratory

Rehabilitation

Patches Bracelets Headsets

Bionics - Implantable Sensors

Neural/Brain

Deep Neuro stimulato

Ear

Vision

Cochlear Implants

Cardiac

Defibrillators/ Pacemakers

Ortopedic

Molecular Diagnosis

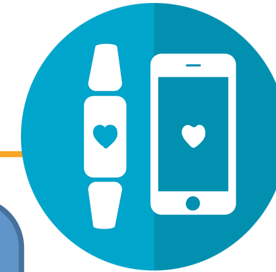
Lab-on-a-chip:

Infectious diseases, cancer, virus, DNA recongnition

Medical Sensor Technology Requirements

- **Good quality signal**
- **Frictionless technology (non-invasive)**
- **Autonomie** ultra-low-power or enegry harvesting
- **Clinical validation** and **user adoption**
- **Safety/ Security** big data storage & computing power (filter, process)
- **Portable** and **very low power**
- **Miniaturization/weight**
- **Biocompatibility** (implanted/absorbed devices), manufacturability and cost
- **Packaging and reliability**

Concept 4: ***Wearables for medical/wellness applications***

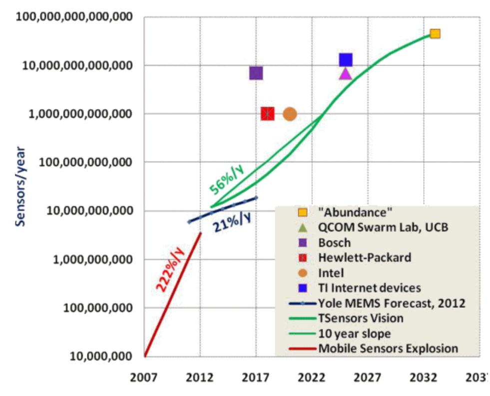


Medical wearable are devices with sensors attached to the body that detect and monitor changes in body signatures of various areas and organs. They feature feature wireless data transmission, real time feedback, alerting mechanisms and better health management

Smart phones, Smart watches, Wrist monitors, Google glasses → Activity & Heart Monitoring

Quantified self's → Trillion of sensor planet → Personalized & preventive healthcare

From smart patches to epidermal electronics



Internet-of-humans

2018 → 2023 → 2026 → 2029 → 2033

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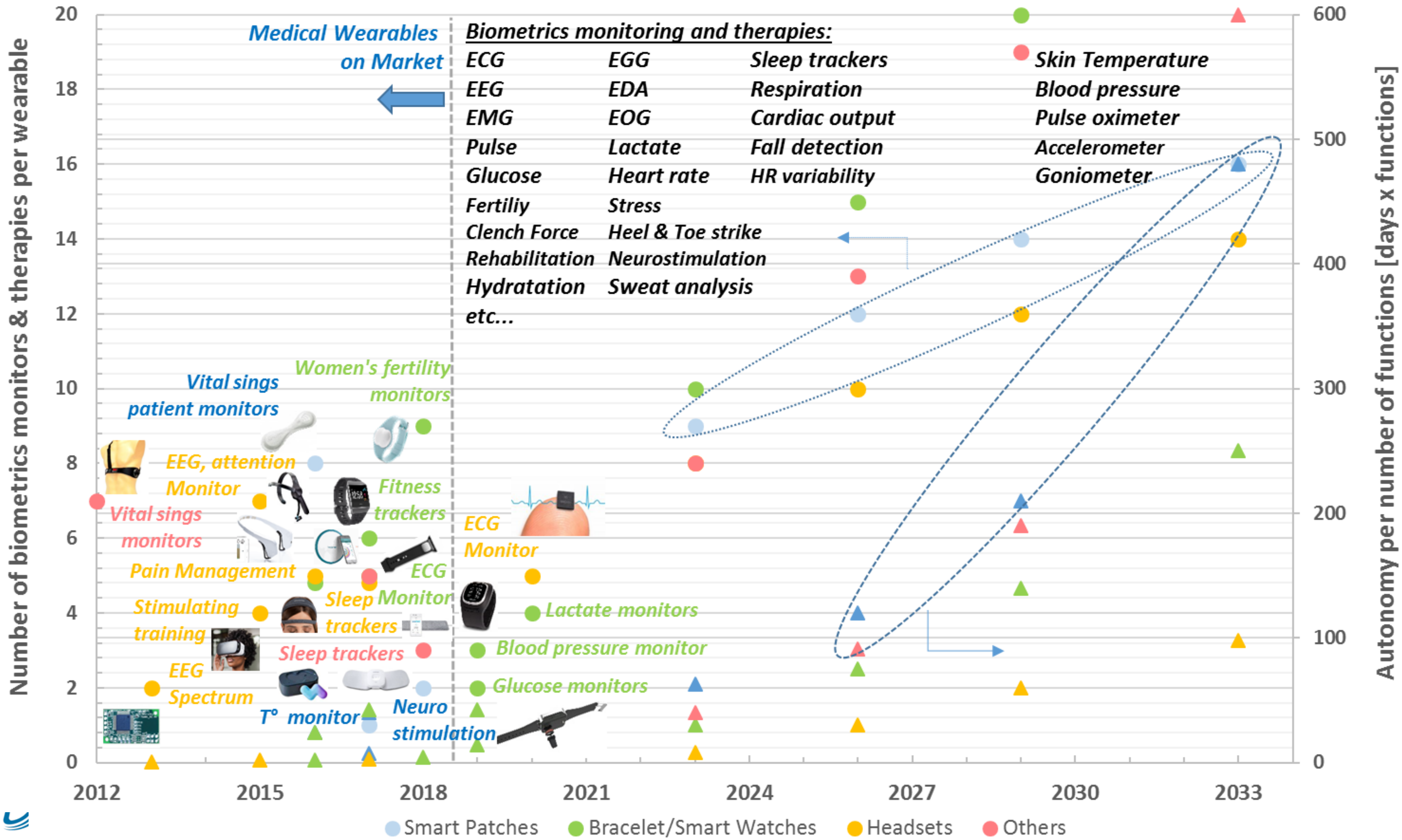
Concept 4: *Wearables for medical/wellness applications*

- **Increase n° of biometrics monitoring**
- **Wearable autonomy** (autonomy per number of functions)

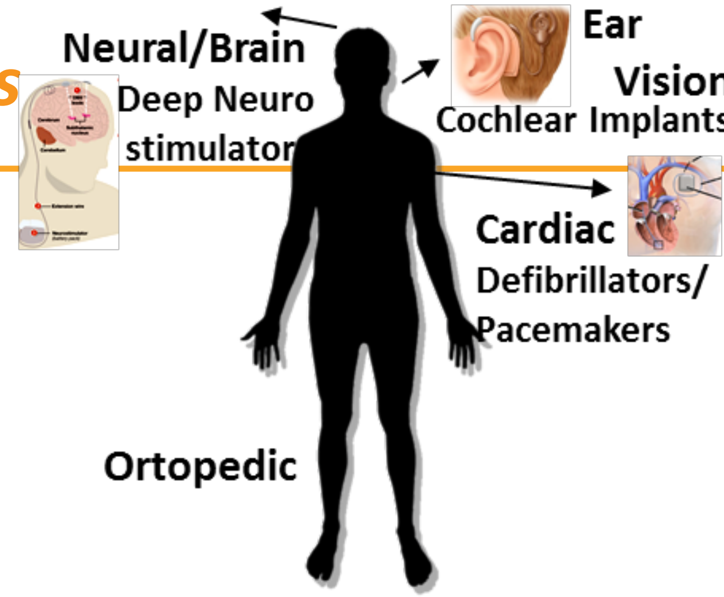


Concept 4: *Wearables for medical/wellness applications*

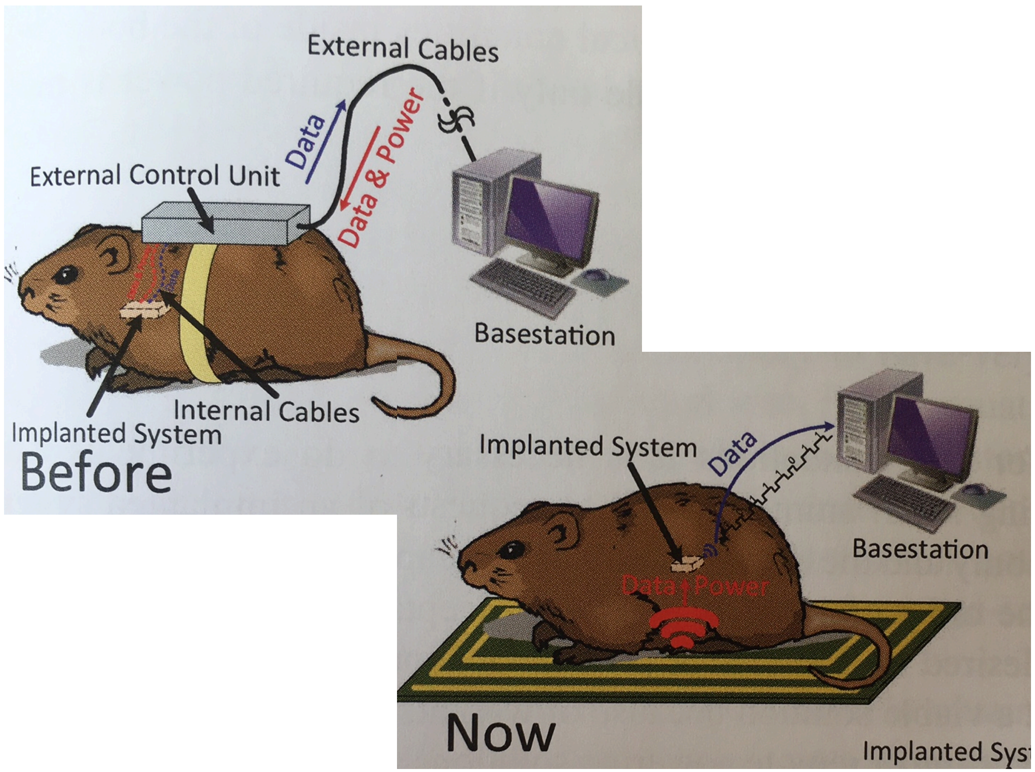
Figures of merit	2023	2026	2029	2033
Sensor element power consumption	< 200 nW	<150 nW	< 100 nW	<50 nW
Sensing time	1 min	50 s.	40 s.	30 s
Resolution	>8 bit	> 9 bit	> 10 bit	>10 bit
Non-invasive	Min. invasion			Fully non-invasive
Multiparameter sensing	Activity parameters + a few biomarkers + air quality monitoring	Full activity + Tens of biomarkers + air quality monitoring	Full activity and energy expenditure + Tens of biomarkers + full environmental monitoring (air quality)	Full activity and energy expenditure + Hundreds of biomarkers + full environmental monitoring (allergens, pollens, etc.) + feedback for behavior engineering
Price (depending on complexity)	Low cost medical patches (~5 Euros) Smart sensing modules in wrist based devices (~10's Euros)	Low cost medical patches (~2 Euros)	Low cost medical patches (~1 Euro) Smart sensing modules in wrist based devices (~10 Euros)	Paid by subscription services
Portability	Yes			Full flexible embedding
Lifetime	Hours to Days	Days to weeks	Weeks to months	Months to years

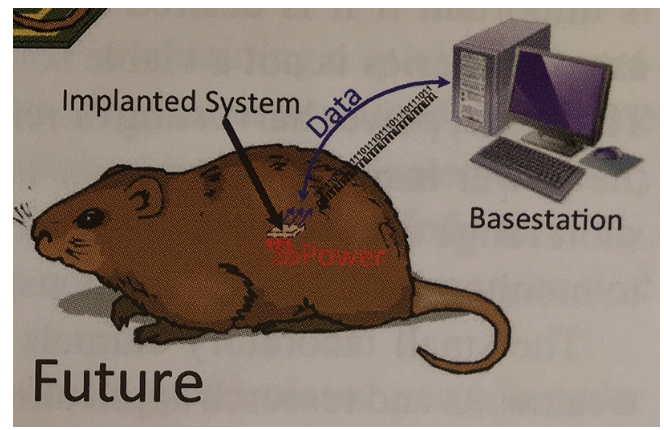
General Recommendation: Cost and convenience (for the patient, the hospital, etc.), Long and tedious development stage

Concept 5: *Bionics – implantable Sensors*



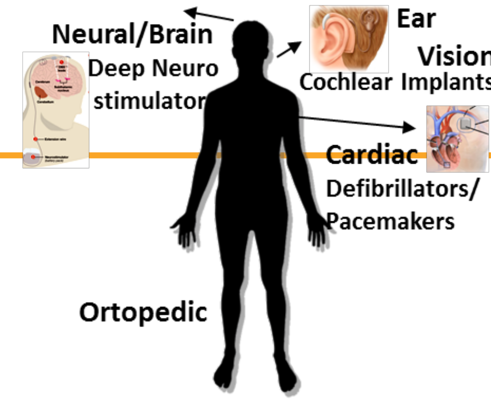
Implantable Medical device is an artifical organs or protheses that take place of malfunctioned organs





Multiple implanted systems communicating one each other

Concept 5: *Bionics – implantable Sensors*



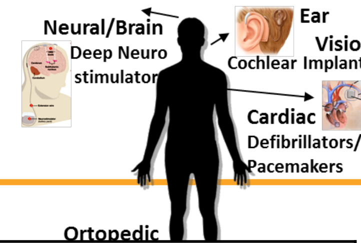
- Improve the quality of health care
- More precise/accurate measurements in the tissue
- Continuous monitoring for a long-term duration

Help to diagnose → better treatment → new therapy strategies / personalized medicine

Main Implantable requirements:

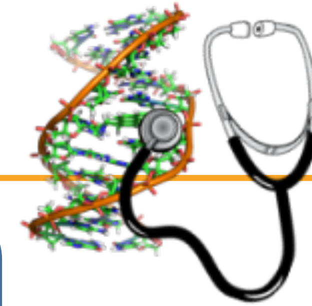
- Increase Lifetime (to reduce n° of surgeries)
- Transcutaneous cables → replaced by wireless power transfer method
- Safety, biocompatibility, bio-stability, reliability → medical system clearance
- Data communication (security and privacy)

Concept 5: *Bionics – implantable Sensors*



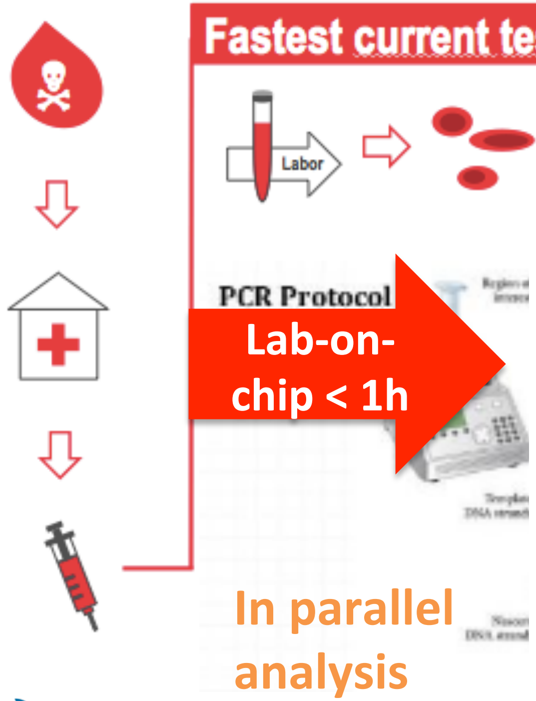
Key research questions or issues	Medium term + 5y	Long term + 15y
Validation tests and certifications (not defined by law yet)	Difficult, expensive and time consuming	Certifications & validation tests defined by law
Specificities of implantable sensors (figures of merit bellow)	Very critical to the final performance	
Technology and design challenges		
Hermetic new package technologies based on flexible polymer	R&D phase	Packaging solutions available
Wireless power supply (overall when the sensor is deep in the body)	Few cm	> 10 cm (ultrasound)
Long-term sensor sensitivity and stability	5 years (A.D.)	10-20 years (A.D.)
Figures of Merit		
Form factor/size	Small, flexible, biomimetic	Biomimetics, strechable
Battery size	Small, flexible	No batteries
Tissue heating	Critical (related to power consumption)	Controlled/solved
Lifetime determine by the long-term sensitivity in order to avoid explantation	A.D. Not relevant for drug releasing devices	1-20 years (A.D.)
Energy harvesting (very limited energy)	Early research	R&D, OK for devices with ultra-low power consump.
Remote/wireless power transmission	Few cm implantation depth using induction.	For >10cm implantation depth alternative
Wireless communication and control	Low data rate/ device works	
Price (determined by local government)	Not critical. Process is very expensive. (e.g. surgery.)	

Concept 6: *Molecular Diagnosis –Lab-on-a-chip*



Molecular diagnostics detect specific sequences in DNA or RNA as genome or proteome. These techniques are used for diagnosis of the various infectious diseases, cancer, and others and is also used to check the genetic predisposition to a disease.

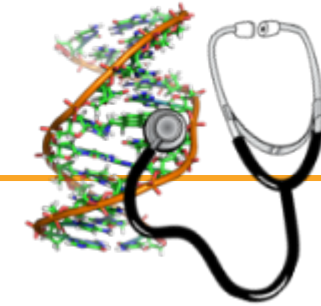
Laborious tests, time consuming and requiring a qualified physician



Impact:

- Monitor diseases more accurately:
  - Allows for early treatment and better patient care
  - Reduce patient morbidity and mortality
- Determine most appropriate treatment:
  - Reduces or eliminates unnecessary/inadequate treatment.
  - Greater cost effectiveness.

Concept 6: *Molecular Diagnosis –Lab-on-a-chip*



Potential for application, Application needs and Impact for Europe	Medium term + 5y	Long term + 15y
Infectious disease, cancer and other disorders medical diagnostic	XXX	XXX
DNA probe/target recognition – Genetic testing	XX	XXX
m-RNA blood screening (for cancerous tumors treatment efficiency)	XX	XXX
Counting of particles/Particle trajectory tracking/Imaging	X	XX
Biological markers analyzer (e.g. acetone in breath for diabetes)	XX	XXX
Single particle or virus detection	XX	XXX
Figure of merit		
Number of parallel diagnostics	20	100
Diagnosis time	1 h	30 min
Price	6000 $	5000 $
Portability	Yes with external equipment	Fully portable

General recommendation: ***It's an application gap that can save life's,***

Highlights of Smart Sensors

Healthcare and automotive are of **high relevance for European industry and research** and Europe is well positioned.

- ❖ Extremely high reliability required (redundancies or failsafe devices), very accurate fabrication and in many cases the **quality is even more important than the price.**
- ❖ **Well-penetrated healthcare system** and favorable regulatory policies.
- ❖ Europe dominates the automonous vehicle market and is reinforced thanks to the presence of **major technology manufactures** and the early commercialization of **ADAS systems.**

Sensors types and challenges relevant for other industrial segments:

- Consumer electronics: **Motion MEMS**
- Industrial: **Image sensors**
- Infrastucture: **Air Quality gas sensors**
- Defense (**LiDAR**), etc.

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Future Healthcare

Disruptive technologies:

- **Molecular** (omics)
- **IoT Smart Sensors**:
  - Biosensor
  - Environmental
  - Nutrition
  - Medical devices
- **Organs-on-chip**
- **Advanced imaging**
- **Data**: storage, integration, security, privacy and standards

Big and deep data: phenotype and genotype
(molecular profiling, medical imaging, lifestyle data)

New generations of models

Human Avatar
(Virtual Patient)

Multi-level, multi-scale, variable complexity

Impact on healthcare, society and economy:

- Personalised Health
- Personalized drugs
- Drug response prediction
- Diagnosis
- Prognosis
- Prevention
- Life style and behavior engineering
- Multi-disciplinary education curricula

Data Infrastructure for healthcare
(security, privacy, ethics)

Conclusions: General Recommendations

*Some of the smart sensor identified gaps by 2030 concern: **manufacturability and cost** (hybrid integration), **low power consumption** (energy efficiency, zero-power or self-powered sensors), **robustness** of design and in production, and **stability & reliability**.*

- **Lack of regulations** and guidelines in
  - Automotive to reduce vehicle emissions and dependence on oil.
  - Medical devices development, clinical validations & FDA approvals
- **Lack metrology and standards** for benchmarking and time consuming
- **Autocalibration** or self-calibrated sensors are crucial
- Sensor packaging, CMOS integration and compatibility (**shared manufacture industry cost** with other applications)
- **Connectivity,** connected objects and Internet of things (IoT)
- **Sensor Fusion** and Wireless Sensor Network (WSN)