NanoElectronics Roadmap for Europe: Identification and Dissemination

3rd General Workshop

Sardinia, June 14-15, 2018

WP5 – System Design and Heterogeneous Integration

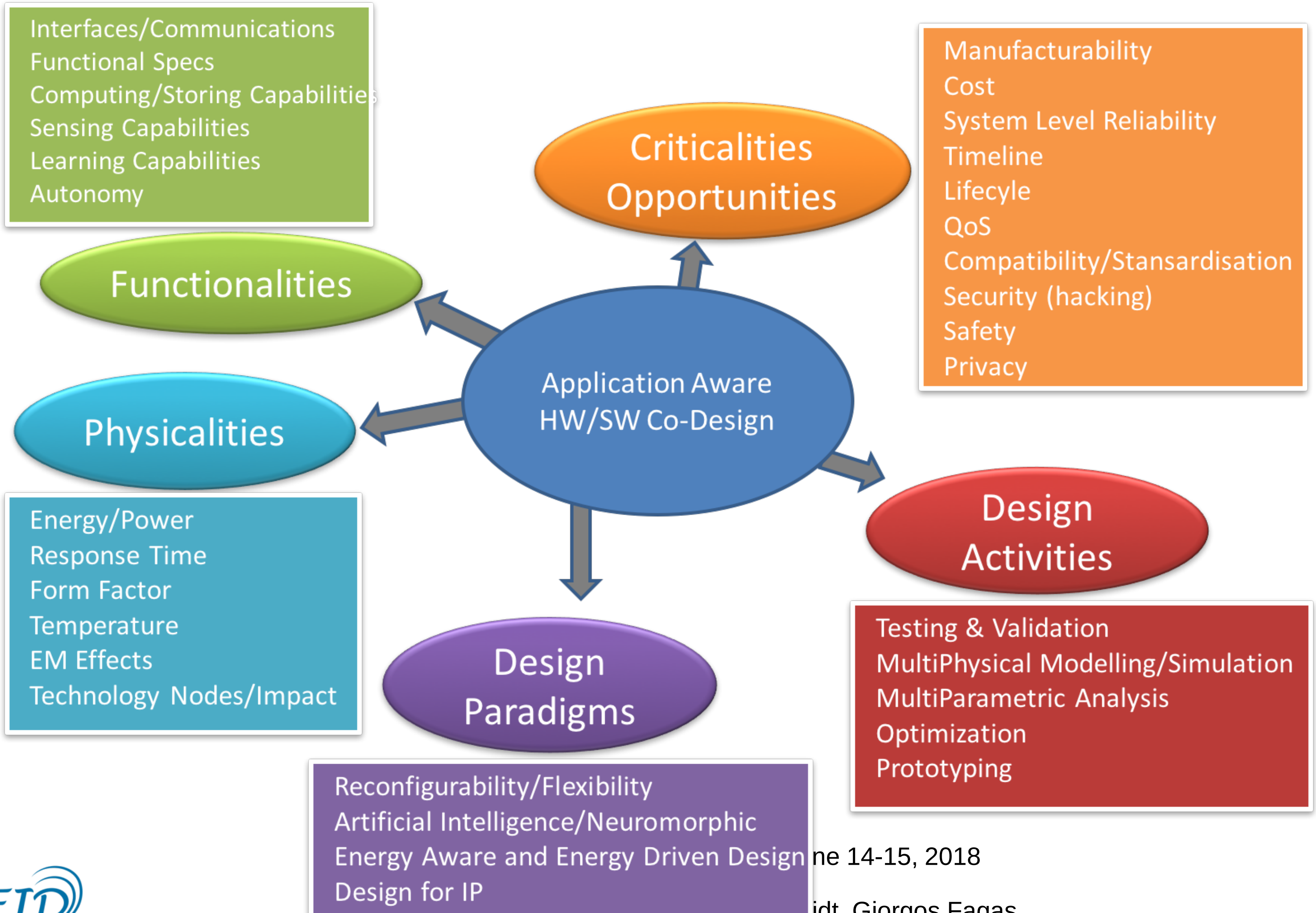
Introduction

- Danilo Demarchi
  - Introduction to System Design and Heterogeneous Integration Roadmap
  - Conceptual approach of the WP5 Roadmap
  - General Table
  - First Application Table: Implantable Bio-Systems
- Holger Schmidt
  - Automotive Megatrends
  - Automated Driving Characteristics and Requirements
  - ADAS / Automated Driving Roadmap
- Giorgos Fagas
  - Environmental Monitoring and Wearable Systems Roadmap
  - Summary of the agglomerated results
  - Extraction of the most important indications
  - Potential for application & Impact for Europe
  - Concluding remarks

Introduction and Implantable Bio-Systems

Danilo Demarchi

The WP5 Roadmap Concept



WP5 Harmonisation

Functionalities
- Specs, Interfaces/Communication, Computing/Storing, Sensing, Learning, Autonomy, Speed

Physicalities
- Energy/power, response time, form factor, environment, temperature, EM effects, technology nodes, robustness

Criticalities & Opportunities
- Manufacturability, Cost, System Level Reliability, Lifecycle, OoS, Compatibility/Standard, Security(hacking), Privacy, Safety, Education

Design Paradigms
- HW/SW, re-configurability, energy aware/driven, design for IP, Open source/cores, Automated

Design Activities
- Verification, testing & validation, multi-physics, multi-parameter, optimisation, prototyping, constraints aware design, …

Energy Autonomy

Connectivity

Sensor Integration

Reliability, Functional Safety & Security

Ubiquitous/ Pervasive

WP5 Harmonisation

Functionalities

- Specs, Interfaces/Communication, Computing, Sensing, Lear Autonomy, S

Physicalities

- Energy/power, response time, form

Criticalities & Opportunities

Privacy, Safety, Education

Design Paradigms

Design Activities

- Verification, testing
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constraints aware design, …

Implementation Qualities

Energy Autonomy

Connectivity

Sensor Integration

Reliability, Functional Safety &

Ubiquitous/ Pervasive

Functionalities

WP5 Map

Everything is Application Driven. The Application drives the choices.		
The Key Functionalities to be considered and measured with their importance and the expected TRL at which after 5+ or 10+ the functionalities have importance	The Implementation Qualities useful for implementing the Functionalities. Measured in 5+ and 10+ importance.	Criticalities & Needs where to indicate the challenges and the needed technologies, measured in 5+ and 10+ horizon, indicating when and how much the technology/solution has to be implemented

WP5 Map

APPLICATION								
FUNCTIONALITIES (*** = Very Important) (TRL to be reached)		IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
- Energy Autonomy - Connectivity - Sensor Integration - Miniaturisation - Reliability & Life Cycle - Functional Safety, Privacy & Security	5+: *? 10+: *? 5+: TRL ? 10+: TRL ?		FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
		PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
		DESIGN METHODS & TOOLS						
		DESIGN PARADIGMS						

The Implemented Roadmaps

- **Application** is the core and the starting point of the roadmap
- Some application domains of reference have been selected:
  - **Implantable Bio-Systems**
  - **ADAS / Automated Driving**
  - **Environmental Monitoring** and **Wearable Systems**, very similar requests in terms of roadmapping

Implantable Bio-Systems - Energy Autonomy

IMPLANTABLE BIO-SYSTEMS								
FUNCTIONALITIES (*** = Very Important) (TRL to be reached)		IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
			FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
Energy Autonomy	*** 5+: TRL 5 for more traditional (batteries) - TRL 3 (for harvesting energy from the body) 10+: TRL 8 batteries - TRL 6 human	PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
		Technology Nodes/Impact on Technology	**	***	2			
		Low power electronics	***	***	4	Design and production of ultra-low power electronics	< μW (circuit consumption)	< nW (circuit consumption)
		Energy storage (e.g., solid state)	***	***	4	Duration	> 10 years	> 30 years
						Recycling of the implantable device	Not applicable	Not applicable
						Recycling of the external supporting electronics (circuit, energy provision, coils, antennas, ...)	***	***
		Energy Harvesting (e.g., new materials)	***	***	4	Energy from outside (energy receivers - antennas, coils, ultrasound, ...) - Related to the request of the implant	mW	mW
						Production of efficient energy from the body	μW	mW
		Energy/Power efficient algorithms	***	***	4	Implementation of efficient energy-aware hw/sw co-design algorithms	**	***
		DESIGN METHODS & TOOLS						
		Automated Design Space Exploration & System Synthesis	*	*	4	Implementation of automated tools for exploring optimal solutions for lowering energy consumption	**	***
						Near/Sub Threshold Design Capabilities	**	***
						Focus of System Synthesis for optimising energy consumption	**	**
		Verification	***	***	4	Verification of system functionalities in case of not stable or critic energy levels	***	***
		Profile of Energy Sources	***	***	4	Design tools for implementing profiling and monitoring of energy sources	***	***
		Constraint Propagation	***	***	4	Tools for propagation of constraints deriving from energy sources, considering their impact on system performances/functionalities	***	***
		DESIGN PARADIGMS						
		Machine Learning Capabilities/Artificial Intelligence	*	*	4	Design for implementing Machine Learning algorithms for optimising power consumption (for example Machine Learning applied in the decision of when and what has to be measured)	*	*
		Energy/Power-driven Design (Energy Transparency)	***	***	4	Application of design paradigms where energy and power are the drivers for design choices in terms both of architecture and fabrication technology	***	***
		Environment-aware Design	***	***	4	Use of design paradigms that consider in design choices the harsh environment (temperature, humidity, acid/basic environment, biocompatibility, ...)	***	***
						Designer Education on new concepts for energy-aware design	***	***
		Neuromorphic Computing / Bio-Inspired (from energy-driven to survival-driven)	**	***	2	Design paradigms inspired by biological systems where is applied the balance power consuption/performance. Adaptation of performances for optimising energy/power consumption	***	***

Implantable Bio-Systems - Energy Autonomy
Physical and Technological Requirements

	FoM 5+	FoM 10+	Link to other WPs
PHYSICAL & TECHNOLOGICAL REQUIREMENTS			
Technology Nodes/Impact on Technology	**	***	2
Low power electronics	***	***	4
Energy storage (e.g., solid state)	***	***	4
Energy Harvesting (e.g., new materials)	***	***	4
Energy/Power efficient algorithms	***	***	4

List of Criticalities and/or needs	FoM 5+	FoM 10+
Design and production of ultra-low power electronics	< μW (circuit consumption)	< nW (circuit consumption)
Duration	> 10 years	> 30 years
Recycling of the implantable device	Not applicable	Not applicable
Recycling of the external supporting electronics (circuit, energy provision, coils, antennas, ...)	***	***
Energy from outside (energy receivers - antennas, coils, ultrasound, ...) - Related to the request of the implant	mW	mW
Production of efficient energy from the body	μW	mW
[illegible] hw/sw co-design algorithms	**	***

Implantable Bio-Systems - Energy Autonomy

DESIGN METHODS & TOOLS						
Automated Design Space Exploration & System Synthesis	*	*	4	Implementation of automated tools for exploring optimal solutions for lowering energy consumption	**	***
				Near/Sub Threshold Design Capabilities	**	***
				Focus of System Synthesis for optimising energy consumption	**	**
Verification	***	***	4	Verification of system functionalities in case of not stable or critic energy levels	***	***
Profile of Energy Sources	***	***	4	Design tools for implementing profiling and monitoring of energy sources	***	***
Constraint Propagation	***	***	4	Tools for propagation of constraints deriving from energy sources, considering their impact on system performances/functionalities	***	***

Implantable Bio-Systems - Connectivity

			FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
Connectivity	* 5+: TRL 6 10+: TRL 8	PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
		Software (external)	*	*	3	Software interfaces for external interconnection of the implantable system (protocol, sw control of transmission power, …)	**	**
		Software (Internal)	**	**	3	Implementation of optimised embedded software solutions for efficient on-board interconnections (sensor data exchange, data collection and storage, …)	**	**
		Bio-Interfaces	***	***	3	Optimisation of electrical interfacing by use of correct materials, geometries and packaging	***	***
		Speed/Latency	*	*	3	Speed of measurements and communication of data	kS/s	kS/s
						Latency in data exchange	ms	ms
		Technology Nodes/Impact on Technology	*	*	2	Importance of connectivity for technological choices	*	*
		Reconfigurability (HW, On-site)	*	*	2	Possibility of on-site HW reconfigurability for changing functionalities and performances	none	none
		Closed-loop Adaptation	*	*	3	Adaptation of communication system with a closed-loop methodology	*	*
		ommunication energy	**	***	3	Consumption per bit	pJ/bit	fJ/bit
						Optimisation of communication channel for minimising power consumption	***	***
		lew materials for antennas (e.g. CNTs, graphene)	**	***	6 & 3	CNTs (biocompatibility issues)	*	*
						Graphene	none	none
		lew materials for low-loss substrates integrating high-onductivity metal interconnects (e.g., PZT, AlN, porous Si)	**	***	6 & 3	PZT	none	none
						AlN	none	none
						porous Si	none	none
		tandardisation	*	*	3	Standardisation of communication protocols for implanted system with external devices	*	**
		DESIGN METHODS & TOOLS						
		Automated Design Space Exploration & System Synthesis	**	***	3	Tools for helping the designer to integrate communication parts with the rest of electronic system	**	***
		Verification	***	***	3			
		Constraints for Systems of Systems	not applicable	not applicable	3			
		Network Verification Tools	*	**	3	Tools for veriying the reliability of the connetivity	*	**
						Tools for verifying efficiency of the connectivity through tissues	**	***
		DESIGN PARADIGMS						
		Machine Learning Capabilities/Artificial Intelligence	*	*	3			
		Environment-aware Design	***	***	3	Application of design paradigms for considering the body environment and its characteristics/parameters	***	***
		Open IPs	*	*	3	Use of Open IPs for developing connecting interfaces of the implantable system	none	none

Considered not so strategic

Implantable Bio-Systems – Sensor Integration

			FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
		PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
		Computing/Storing Capabilities	**	***	4	Computing power	*	*
						Storing capabilities	Mbytes	< 100MBytes
		Sensor Fusion	***	***	4	To be taken from WP4 roadmap		
		Accuracy and Precision	Defined and detailed in WP4					
		Sensitivity						
		Speed/Latency						
		Bandwidth						
		Reconfigurability (HW, On-site)	*	*	3			
		Closed-loop Adaptation	**	***	3	Adaptation of sensing measurements related to the changing environment (temperature, pH, …) & Actuation decisions	***	***
		Calibration	***	***	3	Calibration to be done at system level, integrating all the components	***	***
		Standardisation	**	***	3	Standardisation of sensor interfaces for allowing their use as Ips and qualification for use in the field (FDA)	**	***
		ESIGN METHODS & TOOLS						
		erification	***	***	3	Coverage across domains for verifying intra- and inter-domain interactions	***	***
Sensor Integration	5+: ** 10+: *** 5+: TRL 4 10+: TRL 4	ross Domain Specification	***	***	3	Cross domain simulation tools	***	***
		utomated Design Space Exploration & System Synthesis	*	**	3	Tools for automatising the design of smart and multiple sensors, with their system integration	* (too early, not yet possible)	** (open possibilities due to new standards in sensor design)
		Multiparametric Analysis	**	**	3	Designer Education on System Integration and management of Sensor Fusion	**	***
		Constraint Propagation	***	***	3			
		Functional partitioning	***	***	3			
		DESIGN PARADIGMS						
		Machine Learning Capabilities/Artificial Intelligence	*	*	3	Design for implementing intelligent algorithms for self-adaptation to physical properties of the patient (for example for deciding the best precision and accuracy and/or self-adaptation of thresholds for alarm signal generation)	*	**
						Machine Learning for sensor fusion management	* (implemented externally)	* (implemented externally)
		Environment-aware Design	***	***	3	Design Paradigms for considering in design process the Environment Compatibility	***	***
		Bio-Inspired (from energy-driven to survival-driven)	**	***	2 &3	Implementation of readout circuits for integration inside bio-inspired systems	**	***
			*	**	2 & 3	Implementation of readout circuits for integration inside neuromorphic computing systems	*	**

Implantable Bio-Systems – Sensor Integration

DESIGN METHODS & TOOLS						
Verification	***	***	3	Coverage across domains for verifying intra- and inter-domain interactions	***	***
Cross Domain Specification	***	***	3	Cross domain simulation tools	***	***
Automated Design Space Exploration & System Synthesis	*	**	3	Tools for automatising the design of smart and multiple sensors, with their system integration	* (too early, not yet possible)	(open possibilities due to new standards in sensor design)
Multiparametric Analysis	**	**	3	Designer Education on System Integration and management of Sensor Fusion	**	***
Constraint Propagation	***	***	3			
Functional partitioning	***	***	3			

Implantable Bio-Systems – Sensor Integration

	FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
Computing/Storing Capabilities	**	***	4	Computing power	*	*
				Storing capabilities	Mbytes	< 100MBytes
Sensor Fusion	***	***	4	To be taken from WP4 roadmap		
Accuracy and Precision	Defined and detailed in WP4					
Sensitivity						
Speed/Latency						
Bandwidth						
Reconfigurability (HW, On site)	*	*	3			
Closed-loop Adaptation	**	***	3	Adaptation of sensing measurements related to the changing environment (temperature, pH, …) & Actuation decisions	***	***
Calibration	***	***	3	Calibration to be done at system level, integrating all the components	***	***
Standardisation	**	***	3	Standardisation of sensor interfaces for allowing their use as Ips and qualification for use in the field (FDA)	**	***
DESIGN METHODS & TOOLS						

Implantable Bio-Systems - Miniaturisation

			FoM 5+	FoM 10+	Link to other WPs
Miniaturisation	*** 5+: TRL 5 10+: TRL 8	PHYSICAL & TECHNOLOGICAL REQUIREMENTS			
		Form factor (size, weight, footprint)	***	***	6
		Dimensionality	***	***	6
		Reconfigurability (HW, On-site)	*	*	
		Technology Nodes/Impact on Technology	***	***	2 & 6
		System on flex	***	***	6
		3D (Handling thin die, TSV aspect ratio, inspection tools)	***	***	6
		Flip chip placement accuracy	***	***	6
		Biocompatible and invisible sustainable materials	***	***	6
		Standardisation	**	***	
		Transfer printing, 3D additive manufacturing etc.	Defined and detailed in WP6		
		Thin and large area electronics including R2R, S2S			
		DESIGN METHODS & TOOLS			
		Verification	***	***	
		Automated Design Space Exploration & System Synthesis	*	*	
		Functional partitioning	**	**	
		DESIGN PARADIGMS			
		Design technology co-optimisation	***	***	

List of Criticalities and/or needs	FoM 5+	FoM 10+
Miniaturisation for size critical sensor parts	< 100 um	< 50 um
Miniaturisation for control, power parts, power supplies (batteries)	cm	mm
Minimisation of weight for lowering impact of the implant	< 10 g	g
Optimised footprint of the electronic system to be adaptable in body	cm	mm
Optimisation of 3D dimensionality for lowering impact and increase acceptance	***	***
Process variations impact and related design choices	***	***
Designer Education on impact on design of novel technologies	***	***
Fabrication of flexible and biocompatible susbrates for hosting the full system	***	***
TBD		
TBD		
TBD		
Implementation of standard IPs at System Level and bio-compatible packaging	*	**
Design Rules for Biological Interface, Cross-Domain		
Optimisation for taking in account the biological environment, system level packaging co-design		

Implantable Bio-Systems - Miniaturisation

List of Criticalities and/or needs	FoM 5+	FoM 10+
Process variations impact and related design choices	***	***
Designer Education on impact on design of novel technologies	***	***
Fabrication of flexible and biocompatible susbrates for hosting the full system	***	***

Without batteries (wake up devices from outside)

- Smaller dimensions and lighter
- Orientation of the antenna coil for energy scavenging

These numbers are OK for **devices with batteries**

If rechargeable we need the right antenna orientation

Implantable Bio-Systems – Reliability and Lifecycle

			FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
Reliability & Lifecycle	*** 5+: TRL 7 10+: TRL 9	PHYSICAL & TECHNOLOGICAL REQUIREMENTS				Lifecycle (not relevant for some, very much relevant for others)	> 30 years	> 40 years
						Design of modular systems with respect of the different lifecycle of the parts and the position in body	***	***
						Study of recyclable and/or biodegradable systems	**	***
		Assembly for automation	*	*	6			
		Electro-Magnetic Effects	*	*				
		Mechanical robustness	***	***				
		Accelerated testing	***	***		Development of Acceleration Test	***	***
						Consideration of mixed tests at system level (electronics, communication, bio interfaces and chemical/biological reactions)	***	***
		Operating Environment (temperature, humidity, biofouling, corrosion resistance etc.)	***	***				
		Hermeticity/Insulation	***	***		Study of novel biocompatible materials and packaging techniques	***	***
		Fault tolerance	***	***		Development of self-diagnosic solutions for failure recovering (fail-safe mode)	***	***
		DESIGN METHODS & TOOLS						
		Verification	***	***		Verification of long-term stability of components and system level functionalities/performances	***	***
		Design & Test for Manufacturing	**	**				
		Design for Maintainability/Serviceability	*** (Serviceability only)	*** (Serviceability only)				
		Physics of failure, modelling and virtual testing	***	***		Tools for automatic implementation of fault tolerant systems	***	***
						Tools for virtual and remote testing of the implanted system, no more accessible when installed	**	**
		DESIGN PARADIGMS						
		Reusability (system IPs)	*	*				
		Environment-aware Design	***	***		Novel design paradigms for considering in the design cycle the impact of the environment on reliability and lifecycle of the implanted system	**	***

Implantable Bio-Systems – Reliability and Lifecycle

List of Criticalities and/or needs	FoM 5+	FoM 10+
Lifecycle (not relevant for some, very much relevant for others)	> 30 years	> 40 years
Design of modular systems with respect of the different lifecycle of the parts and the position in body	***	***
Study of recyclable and/or biodegradable systems	**	***
Development of Acceleration Test	***	***
Consideration of mixed tests at system level (electronics, communication, bio interfaces and chemical/biological reactions)	***	***
Study of novel biocompatible materials and packaging techniques	***	***
Development of self-diagnosic solutions for failure recovering (fail-safe mode)	***	***

Implantable Bio-Systems – Functional Safety, Privacy & Security

			FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
Functional Safety, Privacy & Security	*** 5+: TRL 7 10+: TRL 9	PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
		Operating Environment (temperature, humidity, biofouling, corrosion resistance etc.)	***	***		Automatic control systems for detecting dangerous conditions (system failure or hacking)	***	***
		Electro-Magnetic Effects	***	***		Implants compatible with high level imaging tools (MRI, XRay, …)	***	***
		Mechanical Robustness	***	***				
		Reconfigurability (HW, On-site)	*	*				
		Tamper protection	***	***				
		Cyber Security incl. data encryption, transfer protocols and data privacy	***	***		Implementation of specific system parts (HW and embedded SW) devoted to security	***	***
						Designer Education about the regulations and countermeasures to be applied for implementing safe and secure devices	***	***
						Malfuntioning due to hacking activities or unintentional induced reasons	***	***
		DESIGN TOOLS						
		Verification	***	***		Intrusion tests and verification of robustness from external attacks both for data stealing and for system damaging	***	***
						Designer Education about the needed regulations and precautions for safety, privacy & security	**	**
		Automated Design Space Exploration & System Synthesis	*	*		Implementation of design tool modules for automatising the introduction in the system of hw&sw sections dedicated to safety, privacy & security	*	*
		DESIGN PARADIGMS						
		Reusability	*	*				
		Machine Learning Capabilities/Artificial Intelligence	*	*				
		Environment-aware Design	***	***		Novel design paradigms for considering in the design cycle the impact of the environment on safety, privacy & security of the implanted system	***	***

Implantable Bio-Systems – Functional Safety, Privacy & Security

List of Criticalities and/or needs	FoM 5+	FoM 10+
Automatic control systems for detecting dangerous conditions (system failure or hacking)	***	***
Implants compatible with high level imaging tools (MRI, XRay, …)	***	***
Implementation of specific system parts (HW and embedded SW) devoted to security	***	***
Designer Education about the regulations and countermeasures to be applied for implementing safe and secure devices	***	***
Malfuntioning due to hacking activities or unintentional induced reasons	***	***
Intrusion tests and verification of robustness from external attacks both for data stealing and for system damaging	***	***

Tier 2 perspective on WP5
System Design Roadmap for ADAS

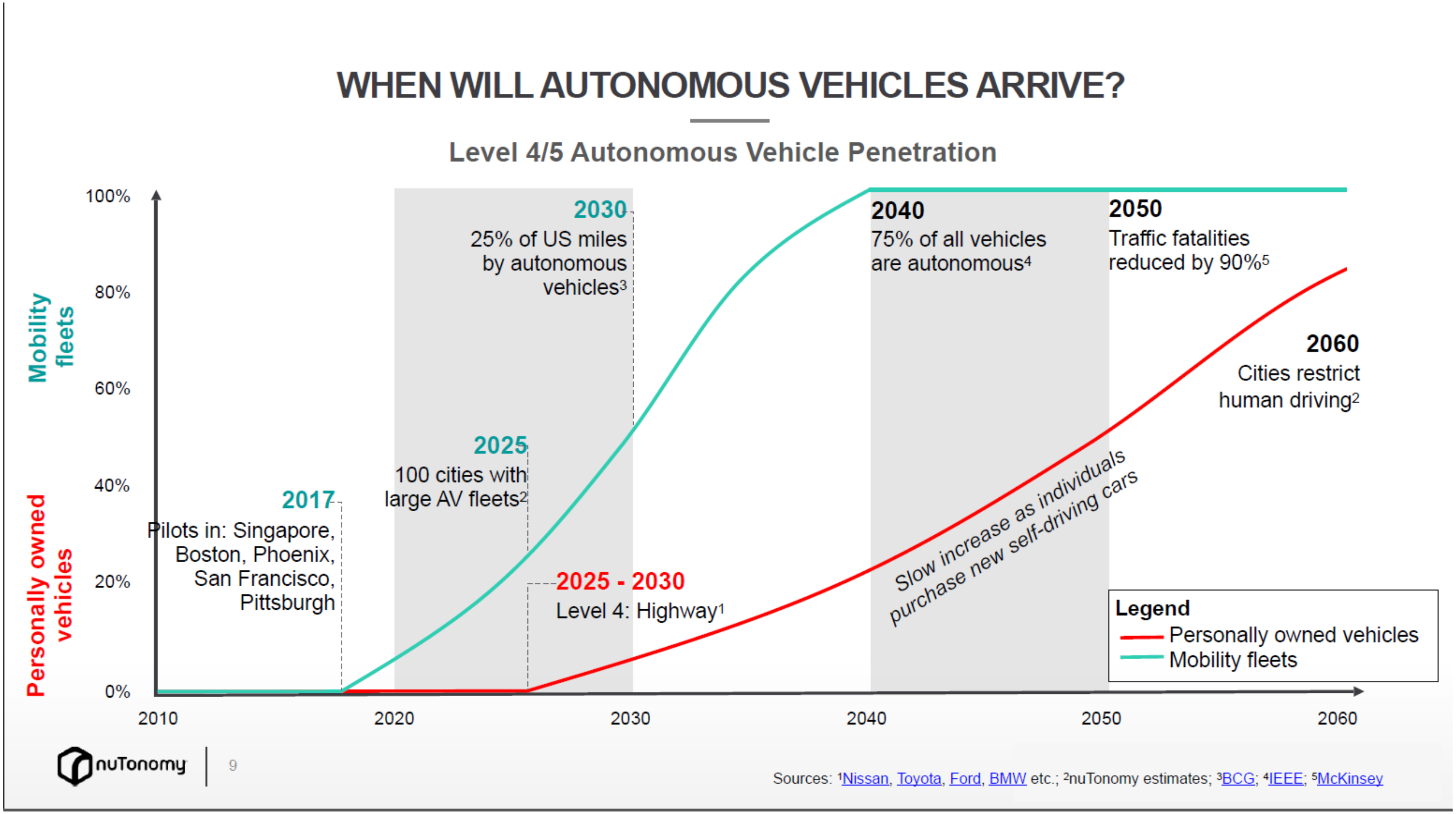
Holger Schmidt

HORIZON 2020

Introduction

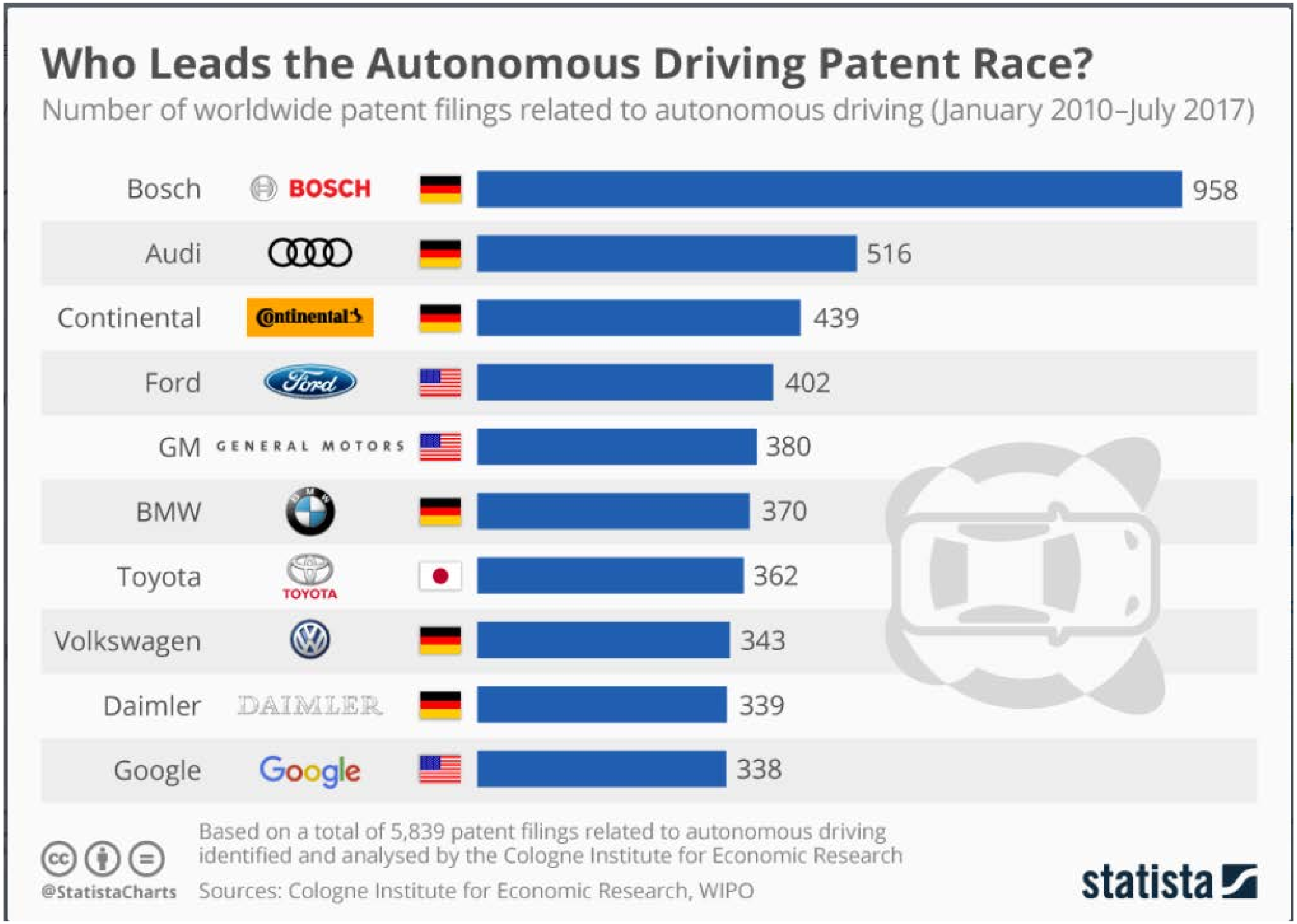
- ADAS Market Perspective
- ADAS System Characteristics
- Roadmap Functionalities and Criticalities
- Conclusion

Market Perspective 1/2

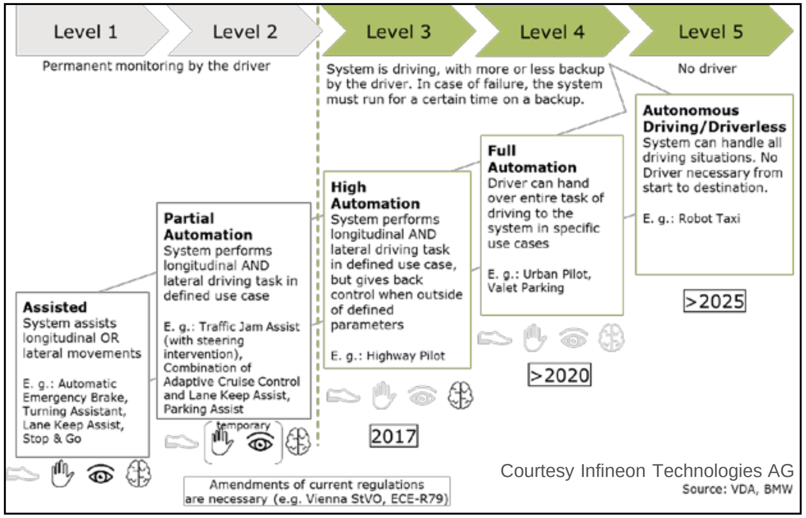


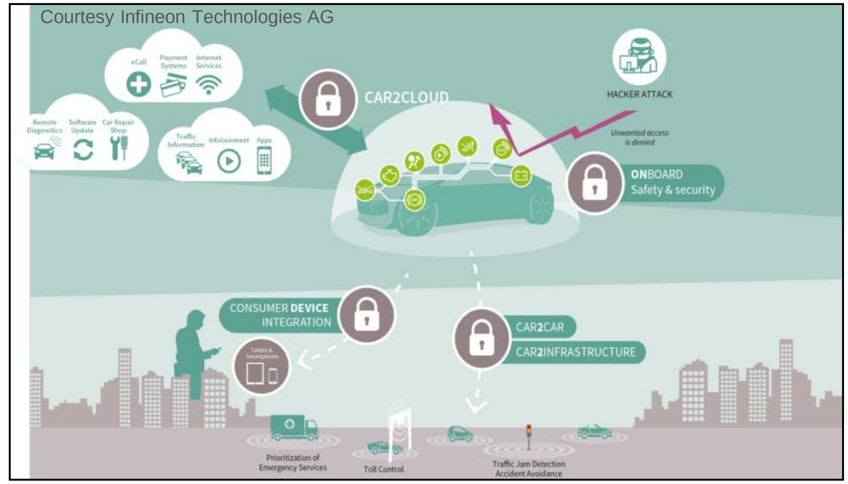
[Source: Autonomy and smart urban mobility]()

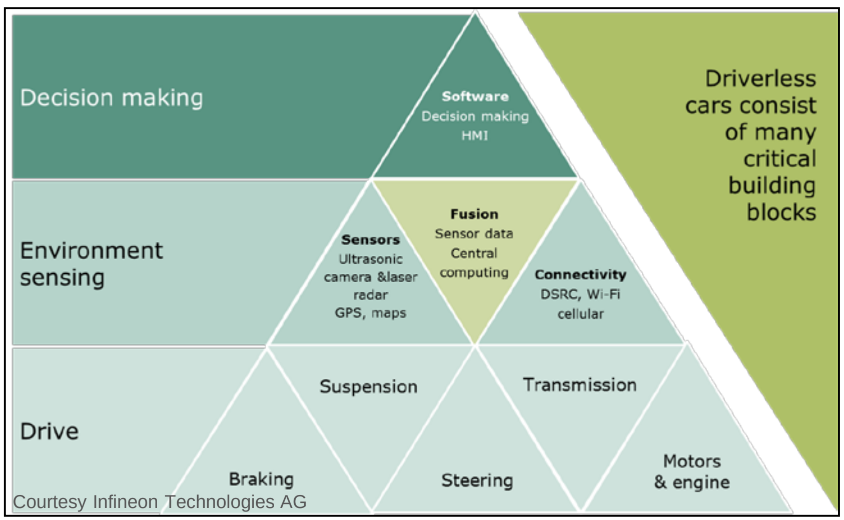
Patent Situation

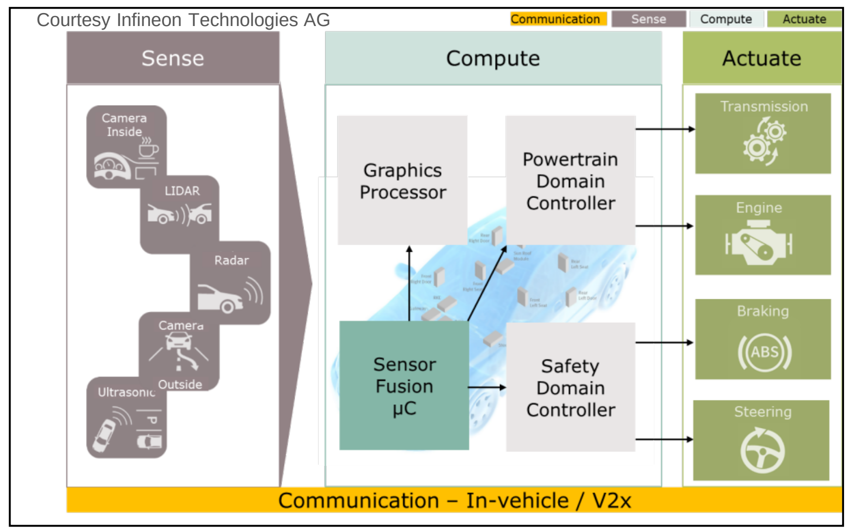


ADAS System Characteristics









Rating of Functionalities 1/2

- **Energy Autonomy, * -> less relevant**
  - low losses / high efficiency are important
- **Connectivity, *****
  - V2x communication; Speed; Latency; Robustness
  - 5G is required
- **Sensor integration, *****
  - Various sensors/MEMS
  - Calibration
  - Sensor fusion

Rating of functionalities 2/2

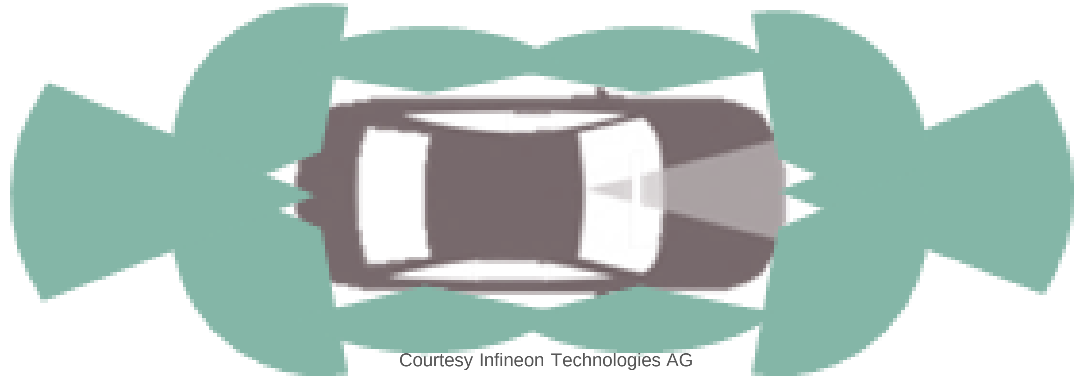
- **Miniaturization, ****
  - Limited space inside a car
  - Weight has to be minimized

- **Reliability & Lifecycle, **(*)**
  - Increasing operation time even for unchanged lifetime
  - Zero defect
  - Automotive requirements and environment

- **Safety, Security , Privacy, *****
  - Fail operational
  - Communication and data have to be protected for an increasing amount of attack scenarios
  - Confidentiality, integrity, authenticity

Example RADAR Criticalities and FOMs

- Short range
- Long range
- Object detection
- …



- Lane assist radar
  - ADC sampling frequency: 10 MHz -> 100 MHz -> 10x
  - Chirp sequence bandwidth increase: 0.3 MHz -> 1.5 MHz -> 5x
  - Total processing gain improvement: 12 dB-> 16x

- BUT: criticalities and needs FOMs depend on
  - System architecture
  - Building block characteristics (ADC type, modulation scheme, …)

Conclusion: Main recommendations

- Need affordable, modular & scalable, evolvable, fail operational, trusted systems
- Ensure and accelerate technologies readyness for automotive
- Support heterogenous integration
- Consider increased operation time (~5x … ~15x)
- Consider higher compute performance at lower power
- Communication: latency 1ms or less, increased bandwidth, lower power
- Support cross domain, cross hierarchy development
- Design, verification, manufacturing and qualification challenge

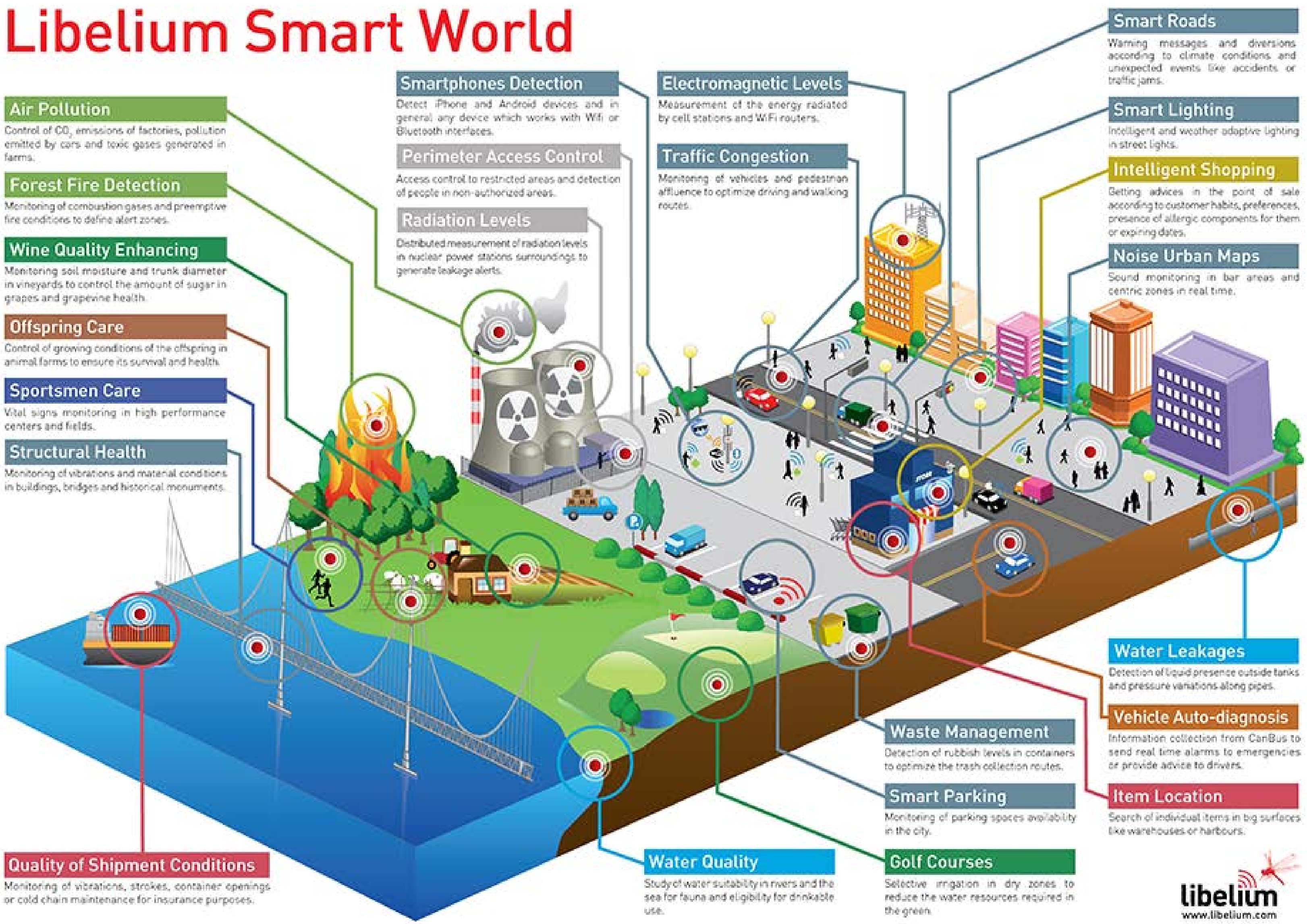
Environmental Monitoring and Wearable Systems Roadmap

Summary of the agglomerated results

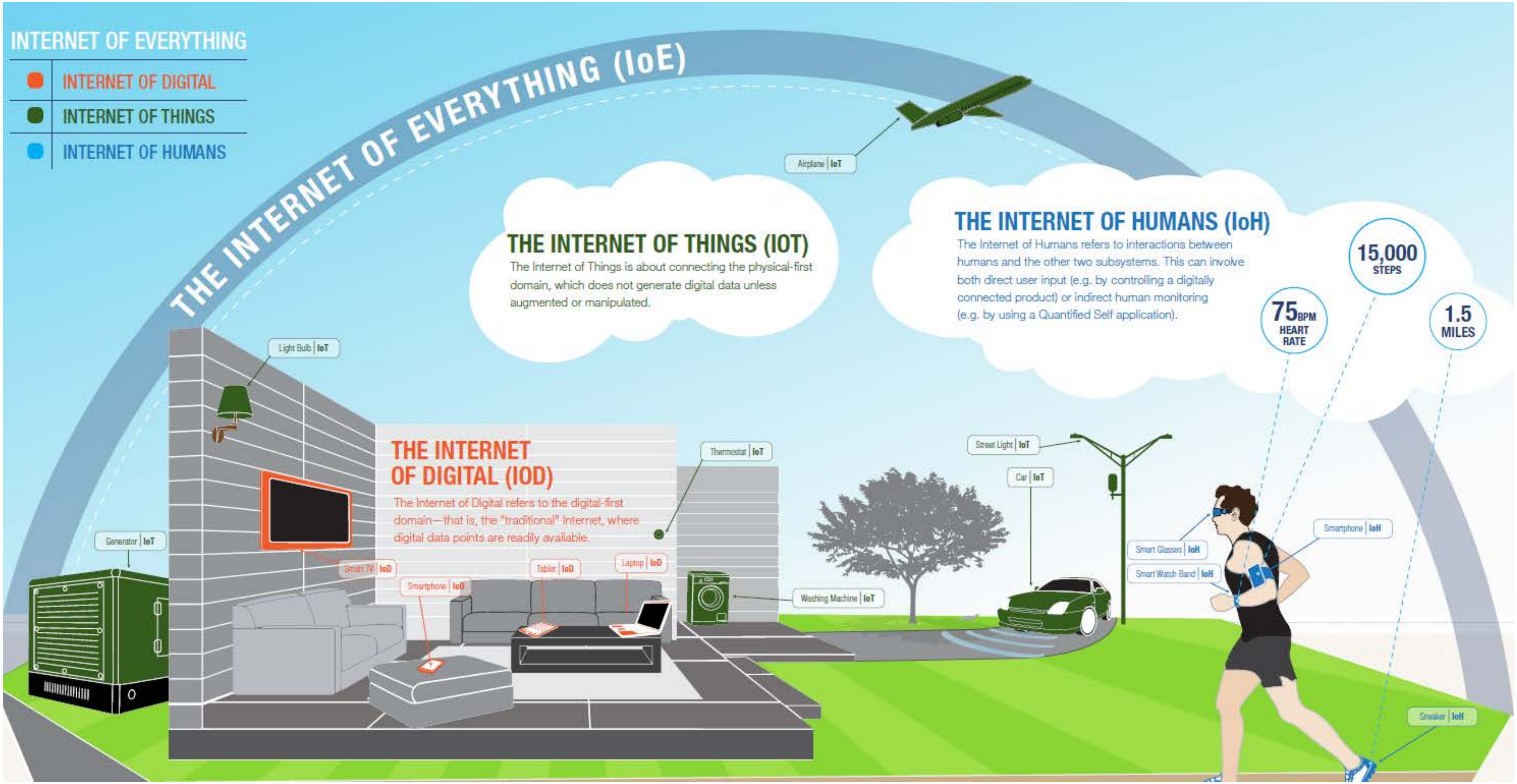
Giorgos Fagas

UN Sustainable Development Goals

Environmental Monitoring Drivers



Wearables Drivers



*** Energy Autonomy – 5+: TRL 5; 10+: TRL 8

IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
	FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
Technology Nodes/Impact on Technology	**	***	2	High Performance Batteries & Fuel Cells for wearables	**	***
Low power electronics	***	***	4	Design and production of ultra-low power electronics	< milliwatts (circuit consumption)	< microwatts (circuit consumption)
Energy storage (e.g., solid state)	***	***	4	Operational lifetime	> 2 years	> 2 years
				Recyclability	***	***
Energy Harvesting (e.g., new materials)	***	***	4	Production of efficient energy harvesters	mW	tens of mW
Energy/Power efficient algorithms	***	***	4	Implementation of efficient energy-aware hw/sw co-design algorithms	20% reduction in energy requirements	50% reduction in energy requirements

*** Energy Autonomy – 5+: TRL 5; 10+: TRL 8

IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
DESIGN METHODS & TOOLS						
Automated Design Space Exploration & System Synthesis	*	*	4	Implementation of automated tools for exploring optimal solutions for lowering energy consumption	Include energy/power parameters in design tools	Energy minimisation through power optimisation
				Focus of System Synthesis for optimising energy consumption	Component/cell level energy awareness	Automated low-power system design
Verification	***	***	4	Verification of system functionalities in case of not stable or critical energy levels	Energy aware self-test	Energy aware self-test & reporting
Profile of Energy Sources	***	***	4	Design tools for implementing profiling and monitoring of energy sources	Behavioural models for power sources	Inclusion of behavioural power models in design flow
Constraint Propagation	***	***	4	Tools for propagation of constraints deriving from energy sources, considering their impact on system performances/functionalities	Identification of constraints and their impact	Energy aware software incl. realistic power

***Energy Autonomy –5+: TRL5 10+: TRL 8

IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
DESIGN PARADIGMS						
Machine Learning Capabilities/Artificial Intelligence	**	***	4	Design for implementing Machine Learning algorithms for optimising power consumption (for example Machine Learning applied in the decision of when and what has to be measured)	**	***
Energy/Power-driven Design (Energy Transparency)	***	***	4	Application of design paradigms where energy and power are the drivers for design choices in terms both of architecture and fabrication technology	***	***
Environment-aware Design	***	***	4	Use of design paradigms that consider in design choices the environment (temperature, humidity, acid/basic environment, biocompatibility, ...)	***	***
				Designer Education on new concepts for energy-aware design	***	***
Neuromorphic Computing / Bio-Inspired (from energy-driven to survival-driven)	**	***	2	Design paradigms inspired by biological systems where is applied the balance power consuption/performance. Adaptation of performances for optimising energy/power consumption	***	***

** Connectivity – 5+: TRL 7; 10+: TRL 9

IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
	FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
Software (external)	***	** *	3	Software interfaces for external interconnection of the wearable system (protocol, sw control of transmission power, …)	**	**
Software (Internal)	* *	* *	3	Implementation of optimised embedded software solutions for efficient on-board interconnections (sensor data exchange, data collection and storage, …)	**	**
Bio-Interfaces	**	***	3	Optimisation of electrical interfacing by use of correct materials, geometries and packaging	***	***
Speed/Latency	*	*	3	Speed of measurements and communication of data	S/s	100 x S/s
				Latency in data exchange	ms	ms
Technology Nodes/Impact on Technology	**	**	2	Importance of connectivity for technological choices	**	***
Reconfigurability (HW, On-site)	*	**	2	Possibility of on-site HW reconfigurability for changing functionalities and performances	*	*
Closed-loop Adaptation	*	*	2			
Communication energy	**	**	3	Consumption per bit	pJ/bit	fJ/bit
				Optimisation of communication channel for minimising power consumption	***	***
New materials for antennas (e.g. CNTs, graphene)	*	**	6 & 3	Performance improvement from new materials	10%	20%
New materials for low-loss substrates integrating high-conductivity metal interconnects (e.g., PZT, AlN, porous Si)	**	**	6 & 3	Area reduction due to new materials	x0.5	x0.1
Standardisation	*	*	3	Standardisation of communication protocols for wearable system with external devices	development of efficient protocols	standardisation

** Connectivity – 5+: TRL 7; 10+: TRL 9

IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
	FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
DESIGN METHODS & TOOLS						
Automated Design Space Exploration & System Synthesis	**	***	3	Tools for helping the designer to integrate communication parts with the rest of electronic system	**	***
Verification	***	***	3			
Constraints for Systems of Systems	**	**	3			
Network Verification Tools	*	**	3	Tools for veriying the reliability of the connetivity	*	**
				Tools for veriying efficiency of the connetivity through tissues	**	***
DESIGN PARADIGMS						
Machine Learning Capabilities/Artificial Intelligence	*	*	3	The intelligence of system is, for example, inside the mobile phone connected to the implantable, so no great intelligence is needed		
Environment-aware Design	***	***	3	Application of design paradigms for considering the on-body and around-the-body environment and its characteristics/parameters	***	***
Open IPs	*	*	3	Use of Open IPs for developing connecting interfaces of the wearable system	none	none

*** Sensor Integration – 5+: TRL 7; 10+: TRL 9

IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
	FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
Computing/Storing Capabilities	***	***	3	Computing power	*	*
				Storing capabilities	Gbytes	Tbytes
Sensor Fusion	***	***	3	Integration and packaging	> 3 (e.g., motion, temperature, bio-signal, air quality)	> 5 (e.g., motion, temperature, bio-signal, UV exposure, alcohol levels)
Accuracy and Precision	Defined and detailed in WP4					
Sensitivity						
Speed/Latency						
Bandwidth						
Reconfigurability (HW, On-site)	**	**	3			
Closed-loop Adaptation	**	***	3	Adaptation of sensing measurements related to the changing environment (temperature, pH, …)	**	***
Calibration	***	***	3	Calibration to be done at system level, integrating all the components	***	***
Standardisation	**	***	3	Standardisation of sensor interfaces for allowing their use as IPs	***	***

*** Sensor Integration – 5+: TRL 7; 10+: TRL 9

IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
	FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
DESIGN METHODS & TOOLS						
Verification	***	***	3	Coverage across domains for verifying intra- and inter-domain interactions	***	***
Cross Domain Specification	***	***	3	Cross domain simulation tools	***	***
Automated Design Space Exploration & System Synthesis	*	**	3	Tools for automatising the design of smart and multiple sensors, with their system integration	* (too early, not yet possible)	** (open possibilities due to new standards in sensor design)
Multiparametric Analysis	**	***	3	Designer Education on System Integration and management of Sensor Fusion	**	***
Constraint Propagation	***	***	3			
Functional partitioning	***	***	3			
DESIGN PARADIGMS						
Machine Learning Capabilities/Artificial Intelligence	**	**	3	Design for implementing intelligent algorithms for self-adaptation to physical properties of the environment	**	**
				Machine Learning for sensor fusion management	**	**
Environment-aware Design	***	***	3	Design Paradigms for considering in design process the Environment Compatibility	***	***
Neuromorphic Computing / Bio-Inspired (from energy-driven to survival-driven)	**	***	2 &3	Implementation of effcient readout circuits	**	***

*** Miniaturisation – 5+: TRL 6 10+: TRL 9

IMPLEMENTATION QUALITIES (*** = Very Important Quality/Concept)				CRITICALITIES & NEEDS (*** = Very Important to solve/implement it)		
	FoM 5+	FoM 10+	Link to other WPs	List of Criticalities and/or needs	FoM 5+	FoM 10+
PHYSICAL & TECHNOLOGICAL REQUIREMENTS						
Form factor (size, weight, footprint)	***	***	6	Miniaturisation for less invasive devices (size)	cm	cm
				Minimisation of weight for lowering impact	~ 100 g	< 50 g
				Optimised footprint of electronics to be adaptable on body	cm	cm
Dimensionality	**	**	6	Optimisation of 3D dimensionality for lowering impact and increase acceptance, lowering powering and increasing S/N	cm3	mm3
Reconfigurability (HW, On-site)	**	**		Inclusion in the integrated circuit of programmable hardware for allowing remote reconfiguration in case of updates or patches	**	**
Technology Nodes/Impact on Technology	***	***	2 & 6	Process variations impact and related design choices	***	***
				Designer Education on impact on design of novel technologies	***	***
System on flex	***	***	6	Fabrication of flexible and recyclable susbrates for hosting the full system	***	***
3D (Handling thin die, TSV aspect ratio, inspection tools)	***	***	6	See WP6 for Manufacturing Technology Details. Remaining challenges are in visualisation of interconnections in 3D structure	SAM, x-Ray	Other?
Flip chip placement accuracy	***	***	6	At medium throughput levels	micron	< micron

Other Functionalities

❖ Reliability & Lifecycle

Very important: ***

5+: TRL 7; 10+ TRL 9

❖ Functional Safety, Privacy & Security

Very important: ***

5+: TRL 7; 10+ TRL 9

Functionalities and Implementation Qualities global ranking

		Global Score		
Functionality	**Implementation Quality**	**FoM 5+**	**FoM 10+**	**Total**
Sensor Integration	Sensor Fusion	9	9	18
Sensor Integration	Calibration	9	9	18
Sensor Integration	Verification	9	9	18
Sensor Integration	Functional partitioning	9	9	18
Miniaturisation	Form factor (size, weight, footprint)	9	9	18
Miniaturisation	Verification	9	9	18
Reliability & Lifecycle	Environment-aware Design	9	9	18
Functional Safety,	Tamper protection	9	9	18
Functional Safety,	Cyber Security incl. data encryption, transfer protocols and	9	9	18
Functional Safety,	Verification	9	9	18
Functional Safety,	Environment-aware Design	9	9	18
Sensor Integration	Computing/Storing Capabilities	8	9	17
Miniaturisation	Design technology co-optimisation	8	9	17
Connectivity	Verification	8	8	16
Sensor Integration	Standardisation	7	9	16
Sensor Integration	Constraint Propagation	8	8	16
Sensor Integration	Environment-aware Design	8	8	16
Miniaturisation	Technology Nodes/Impact on Technology	8	8	16
Miniaturisation	3D (Handling thin die, TSV aspect ratio, inspection tools)	8	8	16
Reliability & Lifecycle	Physical robustness	8	8	16
Reliability & Lifecycle	Fault tolerance	8	8	16
Reliability & Lifecycle	Verification	8	8	16
Reliability & Lifecycle	Design for Maintainability/Serviceability	8	8	16
Reliability & Lifecycle	Physics of failure, modelling and virtual testing	8	8	16

Top Functionalities and Implementation Qualities

Functionality	Implementation Qualities Number	Normalised
Sensor Integration	8	2,00
Reliability & Lifecycle	6	1,03
Miniaturisation	5	0,99
Functional Safety, Privacy & Security	4	0,58
Connectivity	1	0,24

Implementation Quality	Score
Verification	98
Environment-aware Design	78
Automated Design Space Exploration & System Synthesis	50
Standardisation	38
Technology Nodes/Impact on Technology	38
Machine Learning Capabilities/Artificial Intelligence	35
Functional partitioning	32
Reconfigurability (HW, On-site)	30
Constraint Propagation	28

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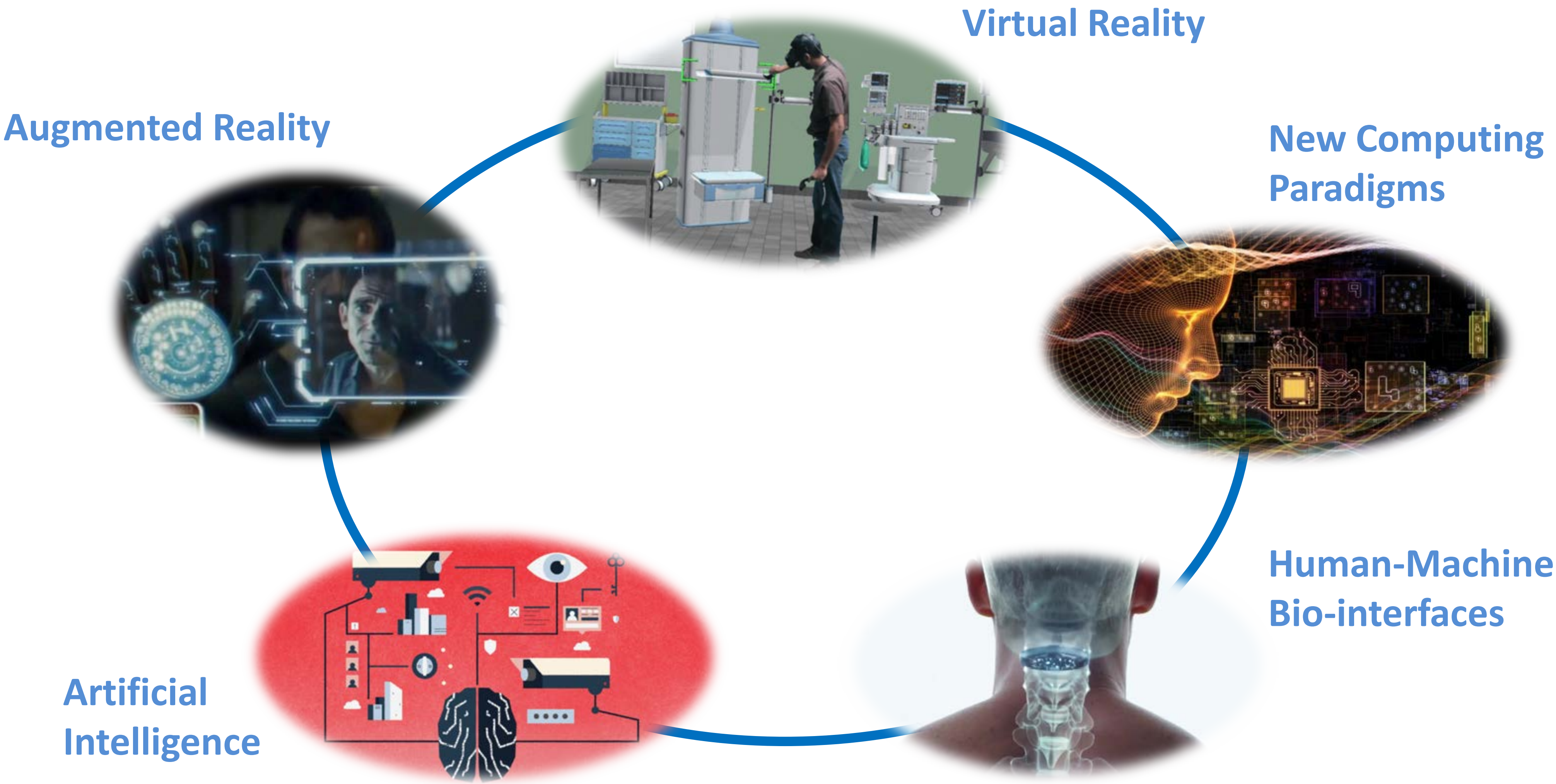
Emerging Trends



Concluding remarks

- **Sensor Fusion** and **Validation** at system level, taking in consideration the environment where the system will operate (**Environment-aware Design**) are considered the most important issues
- In Europe, there are present the most important worldwide stakeholders with original knowledge and developing re-usable platforms, **bringing Europe to a leading position for System Level Applications**
- The strategic conclusion is that it is **for Europe a very good opportunity to drive the increase in System Knowledge and Expertise**