ETH zürich

Research Vectors and Applications of Advanced Mechatronics

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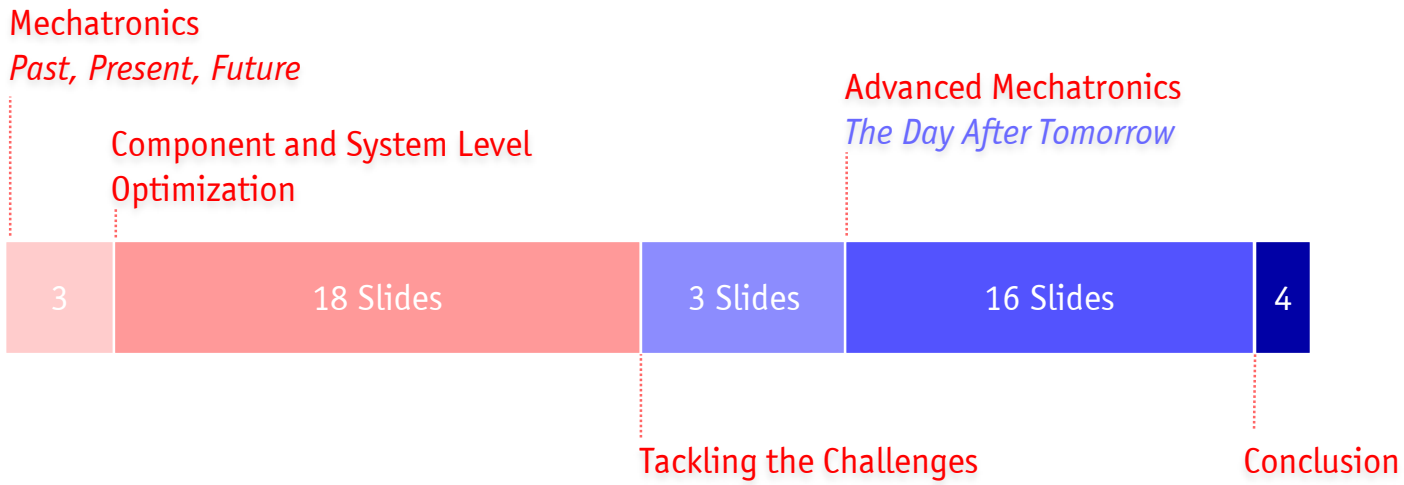
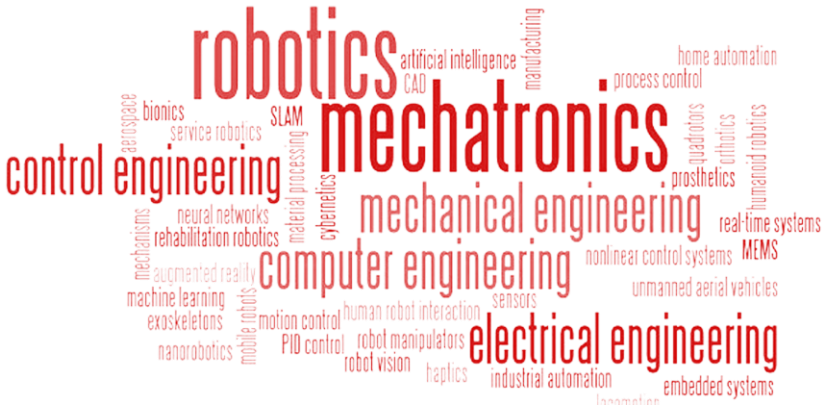
Power Electronic Systems Laboratory
ETH Zurich, Switzerland

Agenda

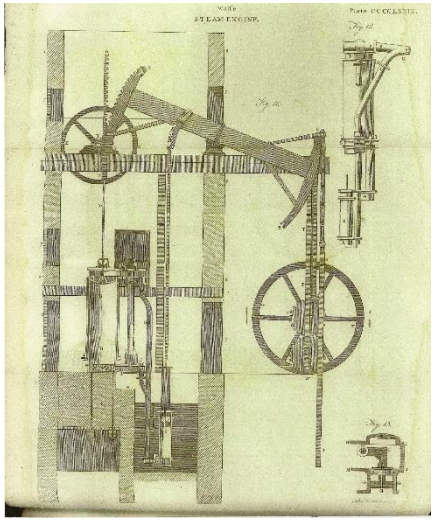

Mechatronics
Past, Present, Future
Component and System Level Optimization
Advanced Mechatronics
The Day After Tomorrow
3
18 Slides
3 Slides
16 Slides
4
Tackling the Challenges
Conclusion

Mechatronics

Past, Present, Future



▶ Development of Motion Control Systems



James Watt's Steam Engine

Integrated Drive System

Digitalization / Internet of Things

■ Exponential Development

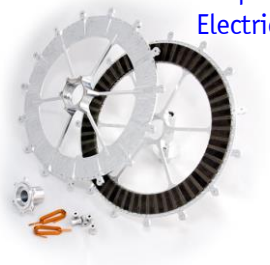
< 1900 Mechanical
1900 Mechanical + Electrical
1950 Mechanical + Electrical + Electronic → **Electronic Motion Control**
1975 Mechanical + Electrical + Electronic + Computation → **Mechatronics**
2000 Mechanical + Electrical + Electronic + Computation + Information Tech. → **Digitalization**

► Future Innovation in Mechatronics: Components and Systems

- 1st Step for Gaining Competitive Advantage:
  Further Optimize the «Component»

High-Precision Sensors

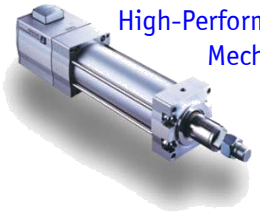
Ultra-Compact & Efficient Electrical Machines



Ultra-High-Speed Electrical Machines

Ultra-Compact & Efficient Converter

High-Speed Digital Signal Processing

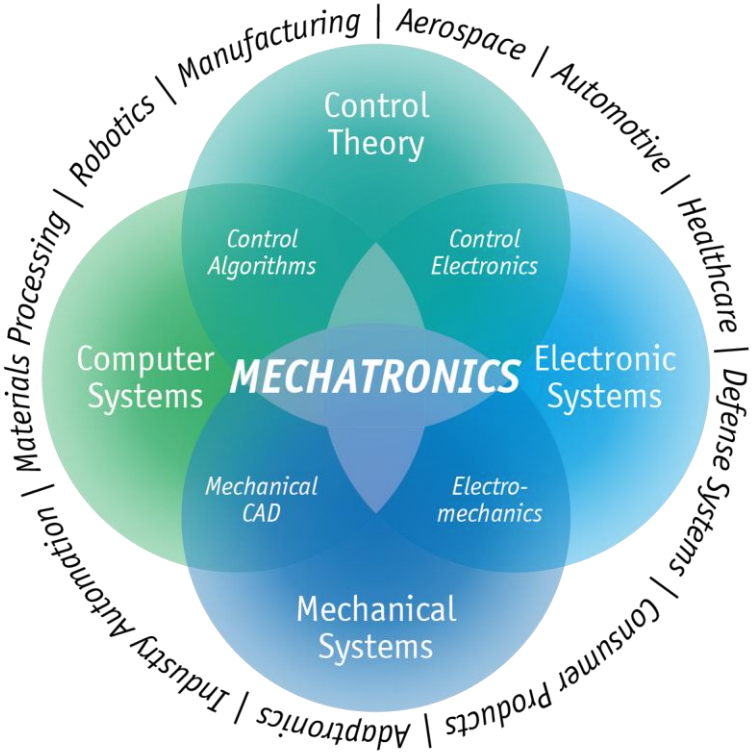


High-Performance Mechanics

► Future Innovation in Mechatronics: Components and Systems

- 2nd Step for Gaining Competitive Advantage:

Target «System Level»

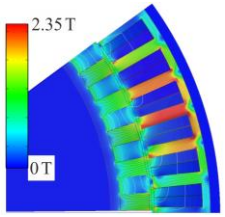


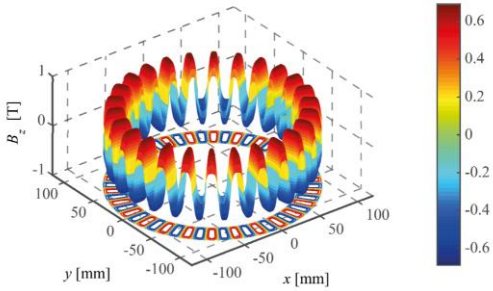
«Component» Level Optimization

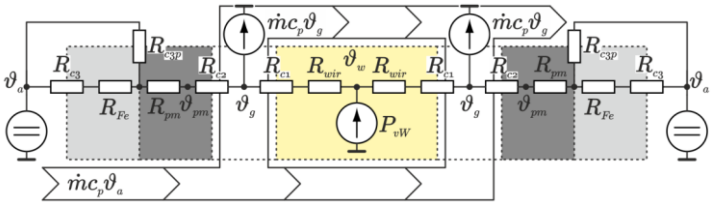
Compact/Lightweight
Efficient
Reliable
Low-Cost
Integrated
..Components

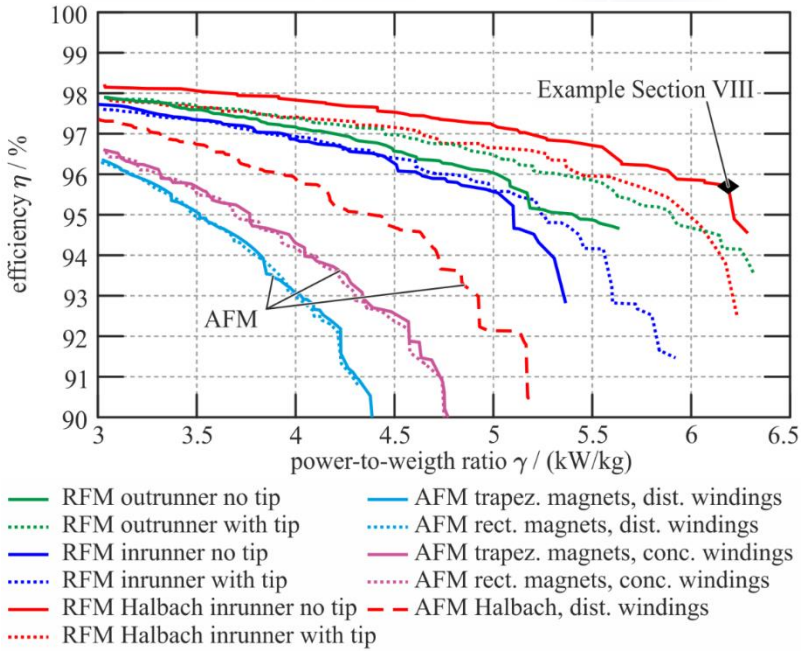
► Lightweight and Highly Efficient Electric Motors

- **Comprehensive Multiphysics Machine Models**
  (Electromagnetic, Mechanical, Thermal)
- **Multi-Objective Pareto-Optimization to find Optimal Design Parameters**







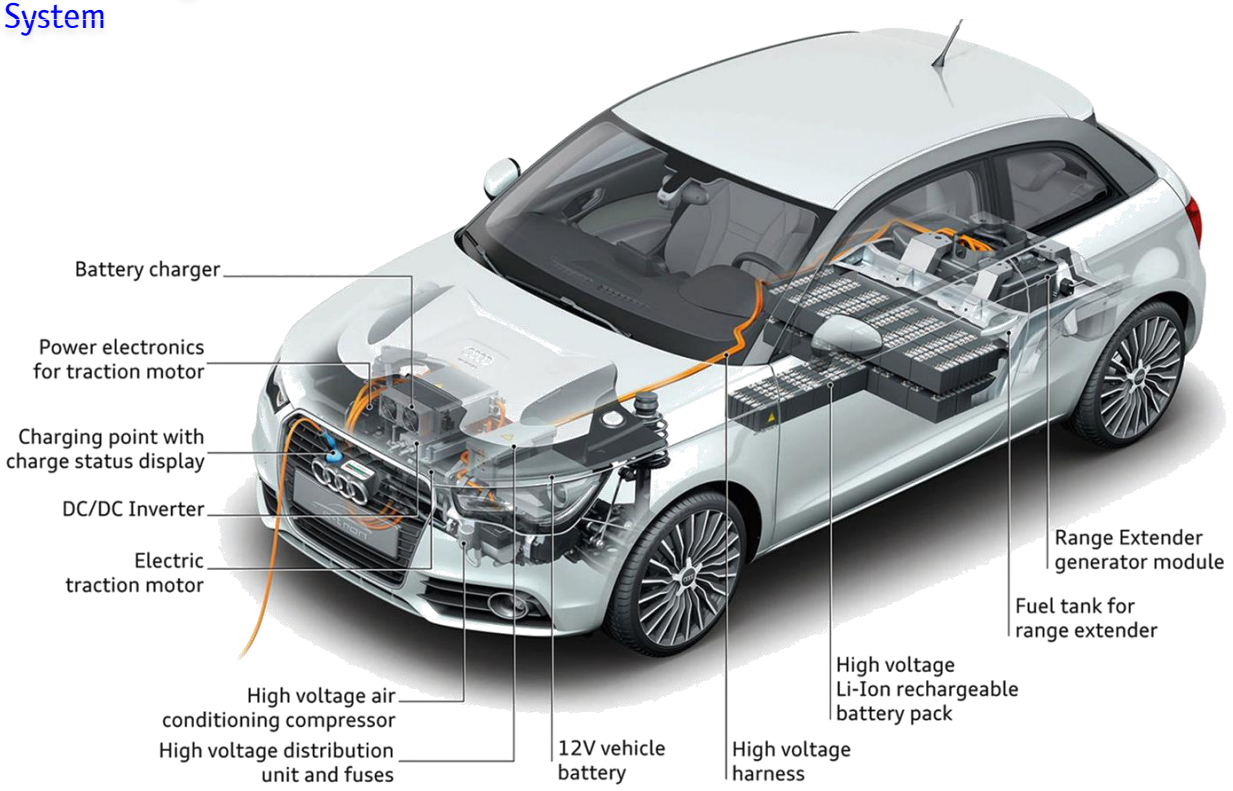


▶ Modern Transportation: E-Mobility

■ High-Performance Components

- Efficient and Lightweight Motor
- High-Power Battery Charger
- Long-Lifetime Batteries
- High-Reliability Battery Monitoring/Protection
- Fault Tolerant Overall System
- ....

■ Integrated Design!



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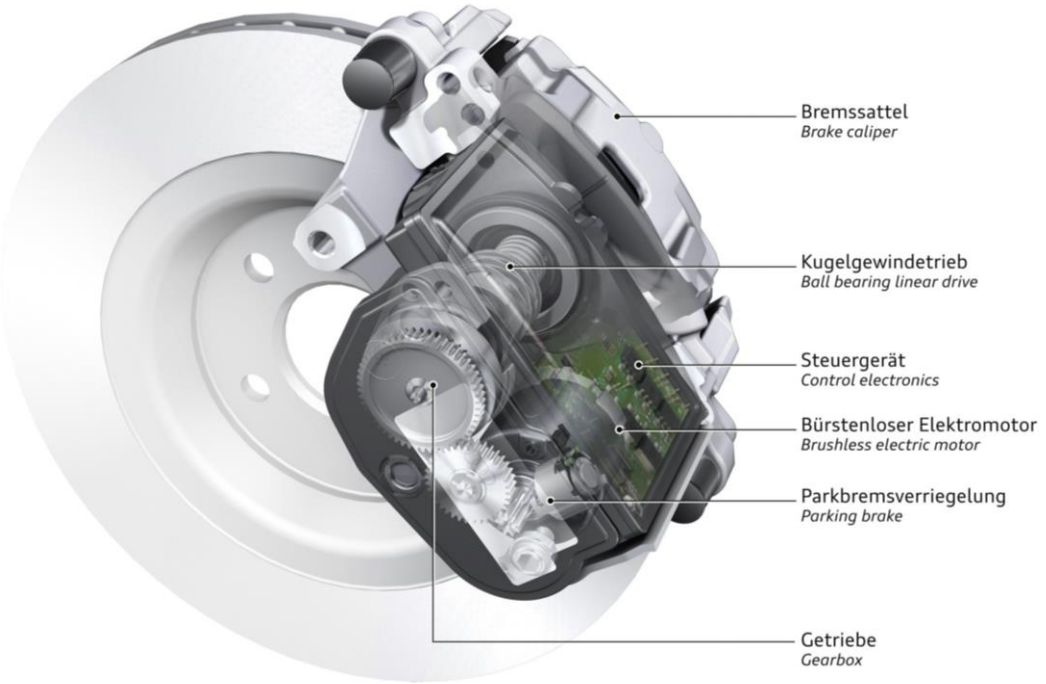
■ Integrated Design

- Power Electronics
- Control Electronics
- Actuators
- Mechanics
- Energy Storage
- Cooling

Audi



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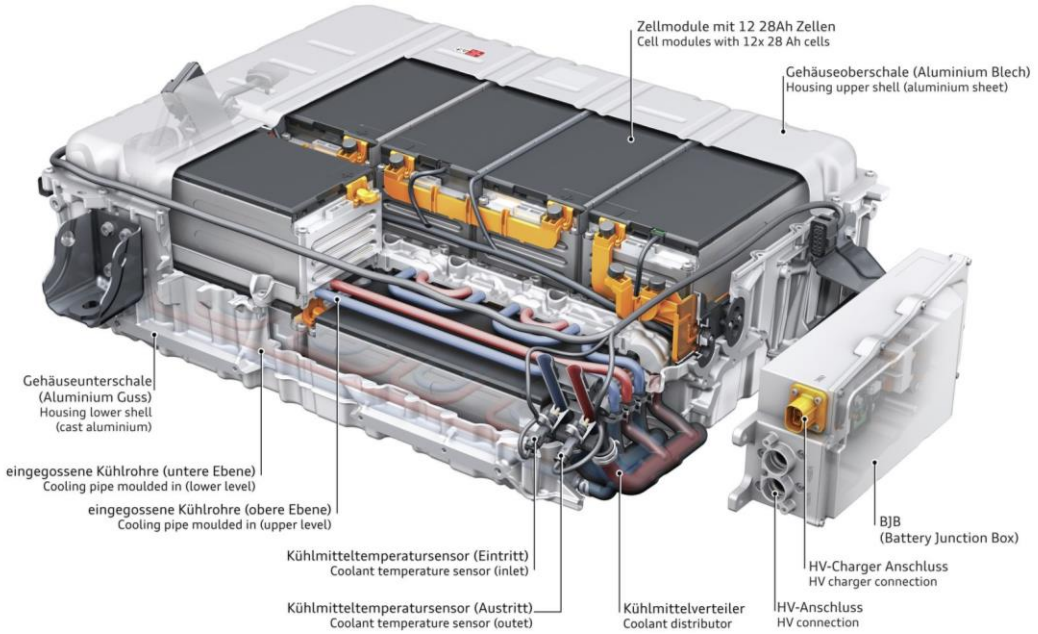

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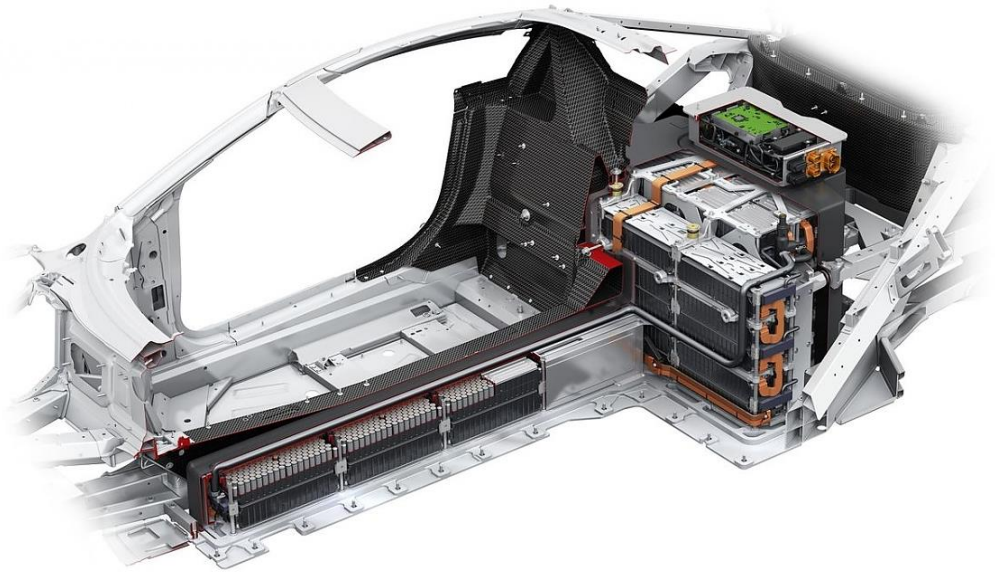

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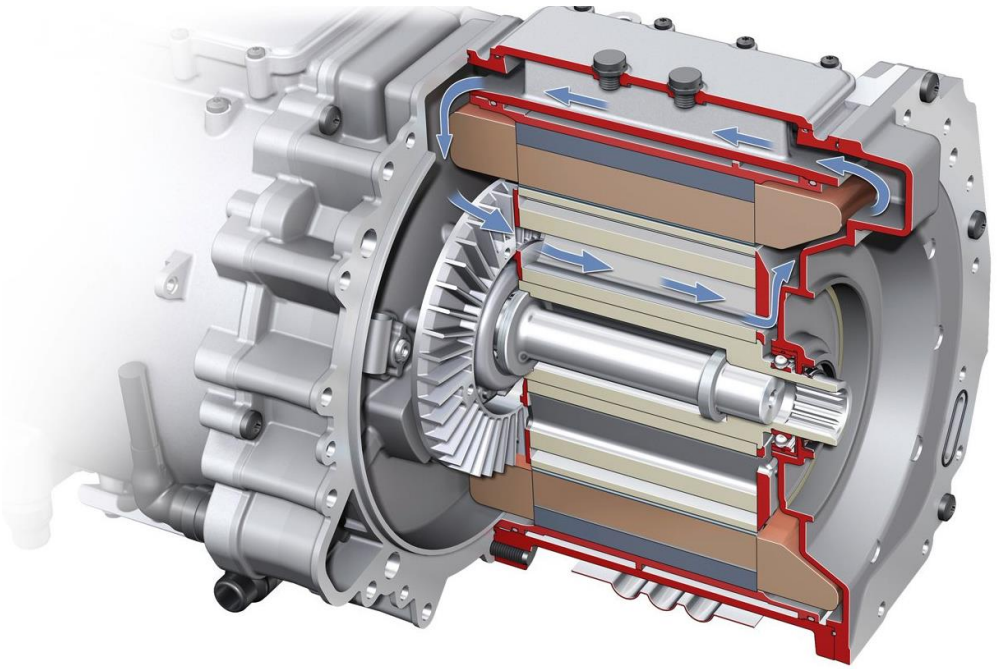


▶ Integrated Cooling for High Power Densities

■ Degrees-of-Freedom for Improved Utilization

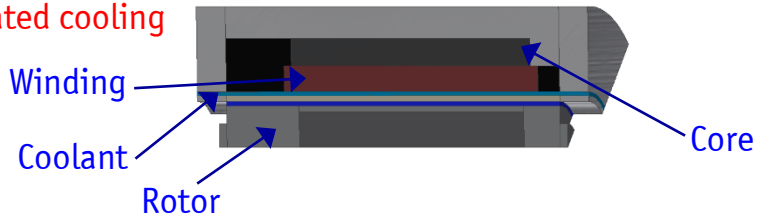
- Manufacturing methods
- Materials
- Cooling

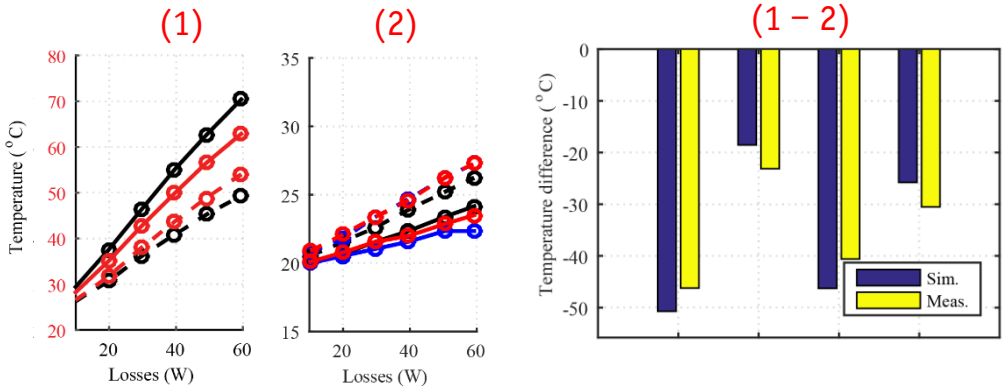
(1) Jacket cooling
(State of the art)

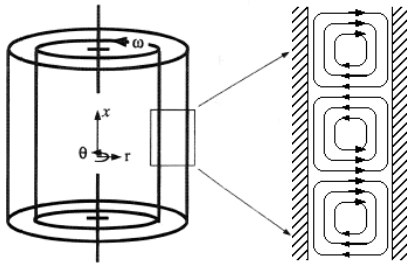
– **Integrated cooling (slotless machines)**

+ Smart design:
  Fast empirical models for cooling
  Magnetic ↔ Mechanical ↔ Thermal
+ > 40 °C hotspot temp. reduction

(2) Integrated cooling





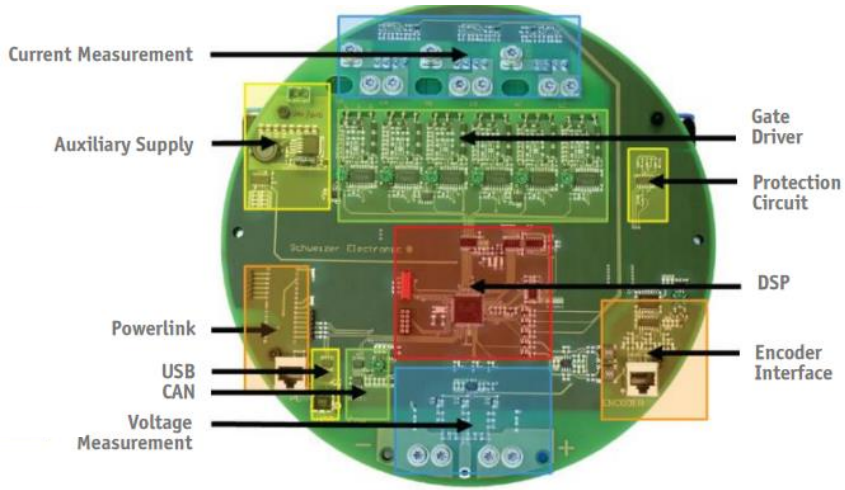


$$Nu_d = f\left(3.66^3 + 0.7^3 + \left(1.615\left(RePr\frac{d}{l_d}\right)^{1/3} - 0.7\right)^3 + \left(\left(\frac{2}{1+22Pr}\right)^{\frac{1}{6}}\left(RePr\frac{d}{l}\right)^{\frac{1}{2}}\right)^3\right)^{\frac{1}{3}}$$

► Integrated Power Electronics in Smart Drives

- **Highest Compactness by Integration**
  - Shorter Connections between Components
  - Common Housing and Cooling System for Motor & Inverter

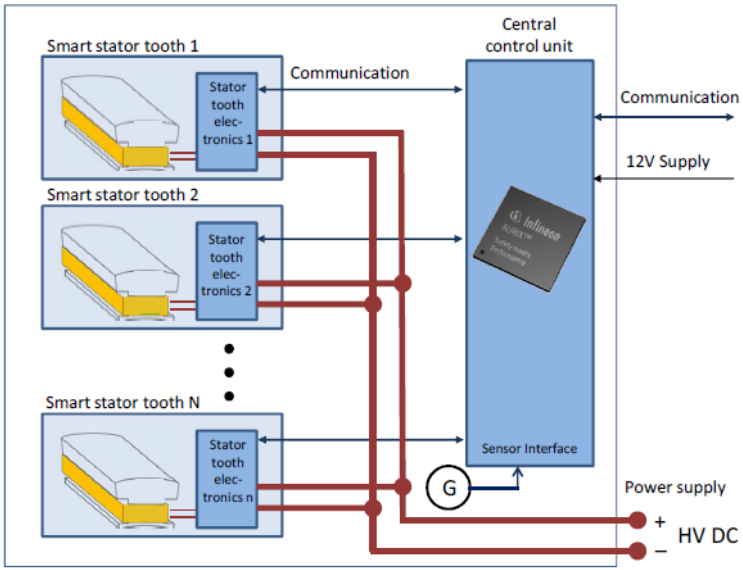
- **3-Phase Si-IGBT Inverter in p²pack-Technology**
  - S_{nom} 32 kVA
  - V_{in} 700 V
  - f_{out} 0 - 800 Hz
  - f_{sw} 20 kHz

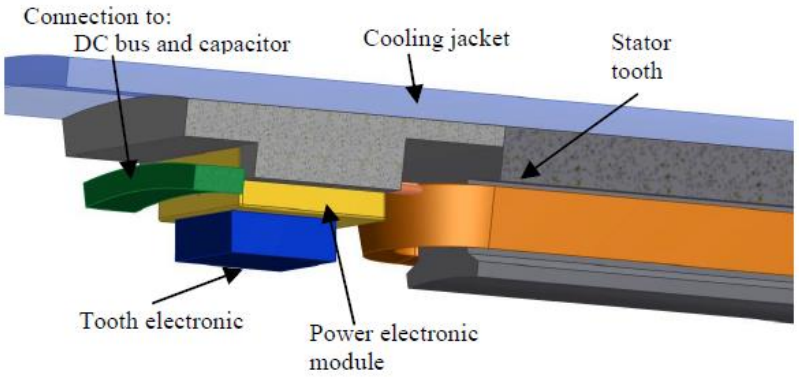


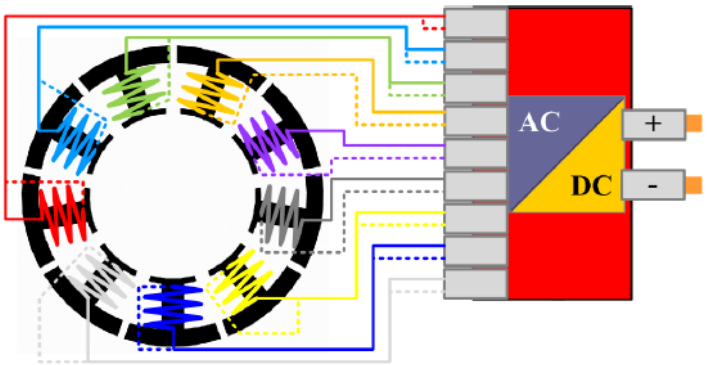
SCHWEIZER ELECTRONIC
enertronics

► Integrated Power Electronics in Smart Drives

- **Smart Tooth Concept**
  - Stator Segment
  - Power Electronics
  - Control Electronics
- **Higher Power Density**
- **Fault Tolerance**
- **Higher Efficiency**
- **Lower Cost**

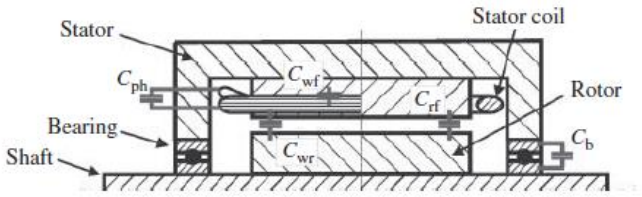




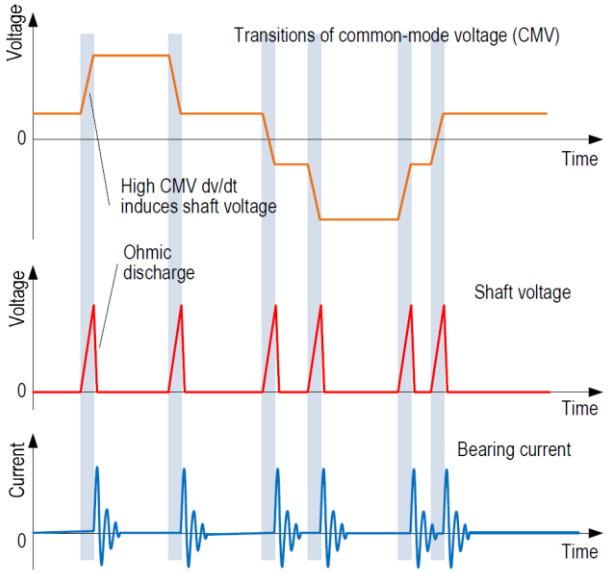


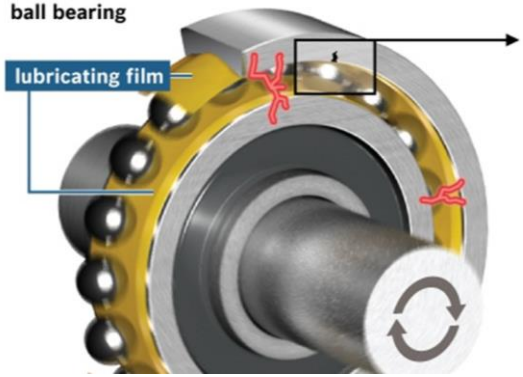
► Low-Maintenance Long-Lifetime Electric Drives

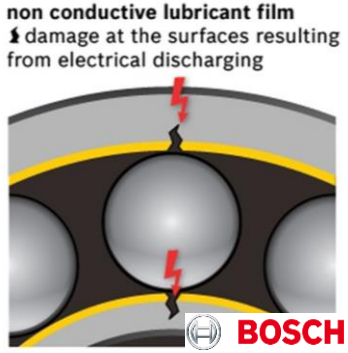
- **Bearing Failure is the Most Common Failure in Adjustable Speed Drives**



- **Bearing Currents**
  - Common-Mode Voltages
  - High dv/dt
  - Parasitic Capacitances
  - Active/Passive Filtering Methods
  - Condition Monitoring/Diagnostics



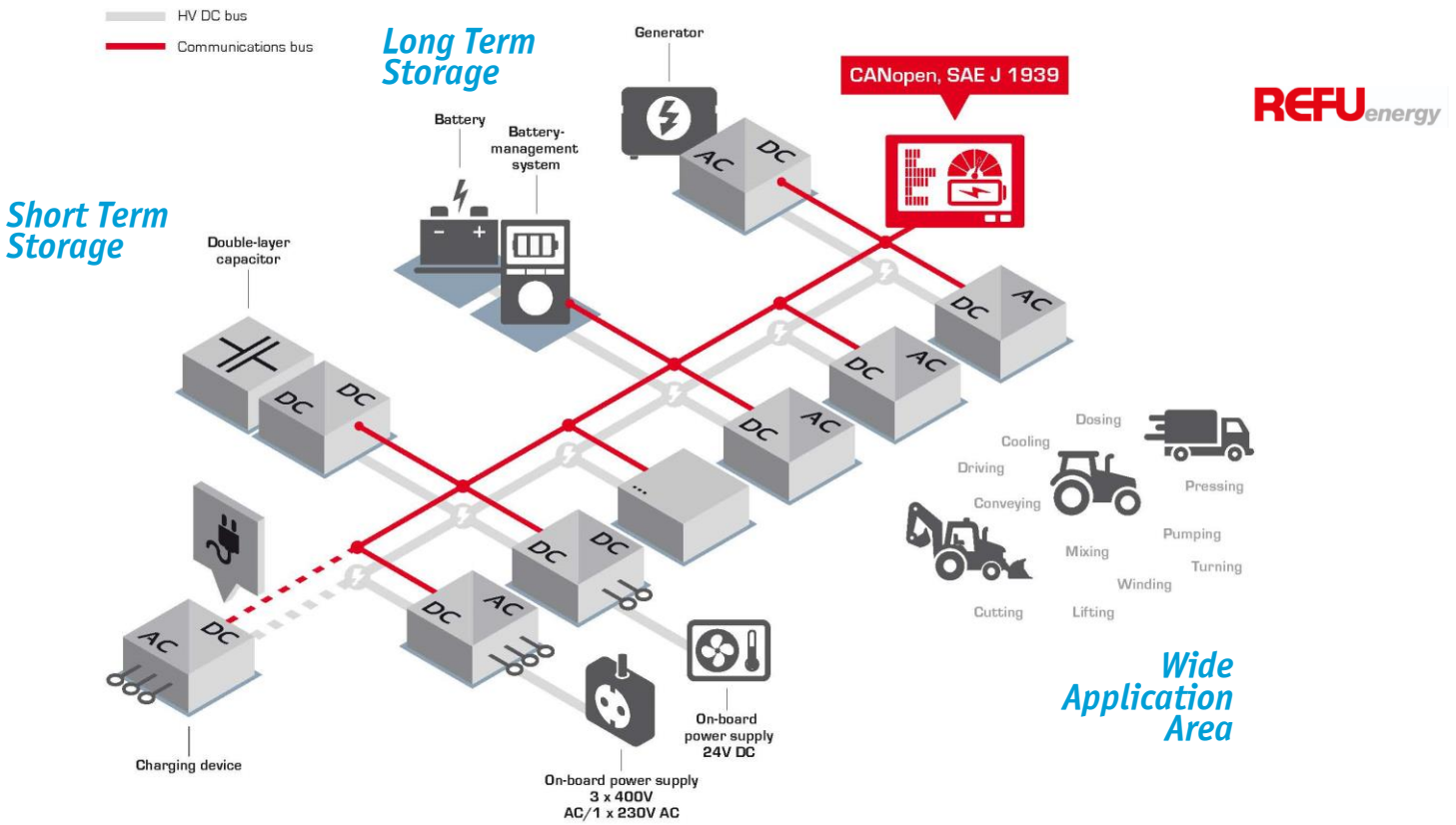




«System» Level Optimization

Hybridization
Electrification
Energy Management
.. of Systems

▶ Electrification of Smart Systems – Energy Management



■ *Smart Power Solutions — Combination of Motors / Actuators and El. Storage*

▶ Layers of Hybridization / Key Competences

■ System-Specific Optimization

■ Target System

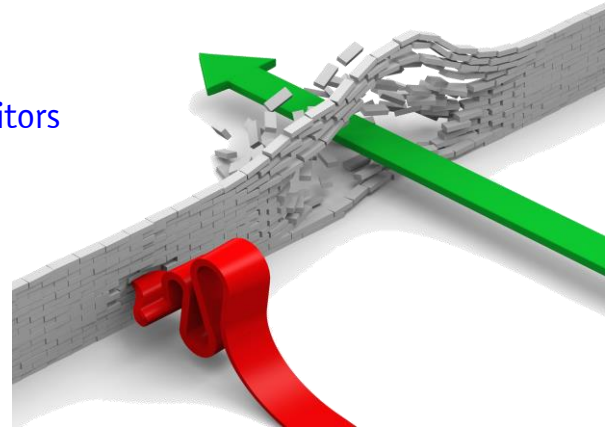
- Heavy Power Fluctuation
- Power Regeneration
- Weak Power Supply/Grid
- Actuators (Machines) with Low Efficiency in certain Operating Regions

■ System Optimization Based on

- Load Profiles
- Present System Structure/Design Freedoms (Limits of Allowed Materials, Operating Conditions,...)
- Performance Goals (Supply Decoupling, Overall Efficiency, Cost,...)

■ Key Competences for a *"Competitive Edge"*

- Batteries (Li-Ion, Lead Acid, Redox-Flow, etc.) and Supercapacitors
- Battery State-of-Charge, Monitoring, Aging
- Modular Power Electronics Converters
- Communication between System Components (Software, ICT)
- Optimal Design Platform for Hybrid Systems

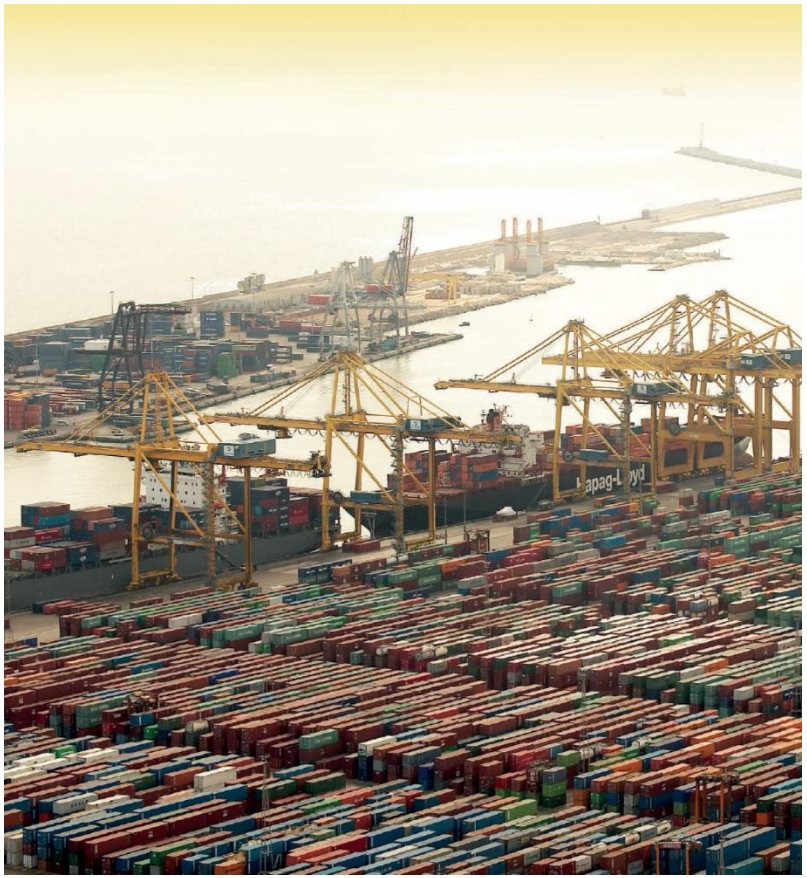


▶ Example #1

REFUenergy

REFUdrive simply lets you move more

- **More efficiency** thanks to energy recovery; maintenance-free and with fuel savings of up to 30 %
- **More safety** based on driverless systems and corresponding integrated functions
- **More precision** in the shape of accurate control technology, the negotiating of bends and torque vectoring
- **More possibilities** based on integrated application functions such as synchronous running, load detection or twin-winch hoists
- **More resistant** thanks to installation of the RPCS in special stainless-steel cabinets or other suitable housings

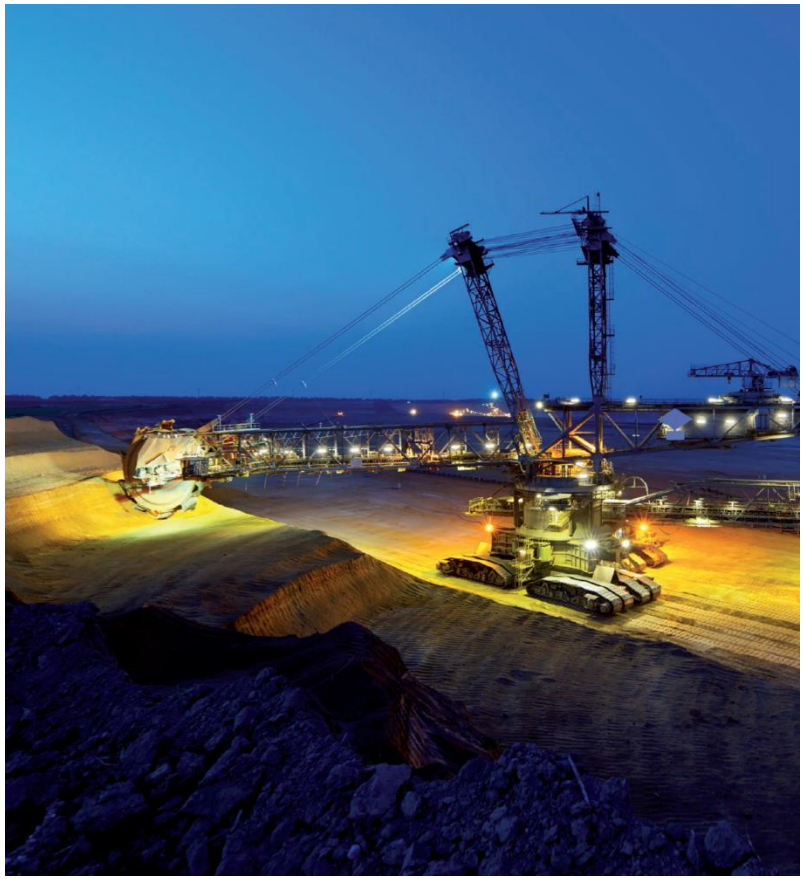


▶ Example #2

REFUenergy

REFUdrive simply lets you move more

- **More reliability** thanks to the resistance of our equipment to shocks and vibrations; even under harsh conditions
- **More efficiency** thanks to the avoidance of energy wastage when braking
- **More safety** thanks to energy recovery, which avoids overheating and helps prevent explosions
- **More savings** thanks to downsizing and energy recovery, along withpeak shaving when operating on batteries
- **More ease** of use thanks to an integrated SPC function that removes the need for expertise on control systems when starting up the machine for the first time



▶ Example #3

REFUenergy

REFUdrive simply lets you move more

- **More environmental** awareness thanks to reduced pollution and lower noise emissions
- **More flexibility** thanks to greater precision in the control of processes and extendable operating times, including at night
- **More safety** for site workers thanks to the prevention of exhaust emissions
- **More cost-savings** thanks to downsizing and reduced fuel consumption
- **More energy** thanks to peak shaving, even with the temporary operation of mains-powered stationary systems

▶ Example #4

REFUenergy

REFUdrive simply lets you move more

- **More autonomy** thanks to optimised work processes that do not depend on the turning speed of a diesel engine
- **More deployment** possibilities thanks to suitability for use in enclosed spaces and unrestricted access to city centres and environmental protection zones
- **More freedom** thanks to the extended operating times made possible by reduced noise emissions
- **More cost-effective** thanks to enhanced efficiency, top battery-powered performance and the downsizing of diesel generators

▶ Example #5

REFUenergy

REFUdrive simply lets you move more

- **More environmental** protection thanks to lower noise pollution and reduced CO2 emissions
- **More flexible deployment** thanks to reduced exhaust emissions and the resulting possibility of use in enclosed spaces and pollution-control areas
- **More possibilities** thanks to a control circuit board with a freely configurable interface and SPC functions
- **More yields** thanks to the matching of production processes to actual circumstances
- **More efficiency** thanks to the use of renewable energy

Tackling the Challenges

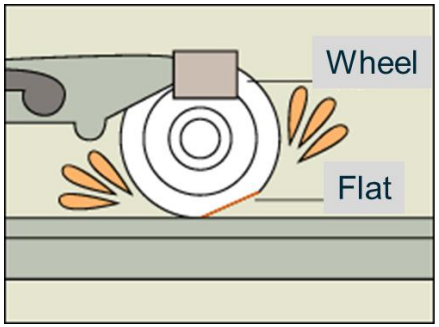
- *Electromechanical Energy Harvesting*
- *Advanced Motion Control*

► Energy Harvesting in Railway Applications (1)

- **Wheel Lock During Braking**
  - Cost of Repair
  - Downtimes
  - Replacement Costs

- **Anti-Lock Braking System (ABS)**
  - Electrical Power Not Available for Controller on Freight Wagons

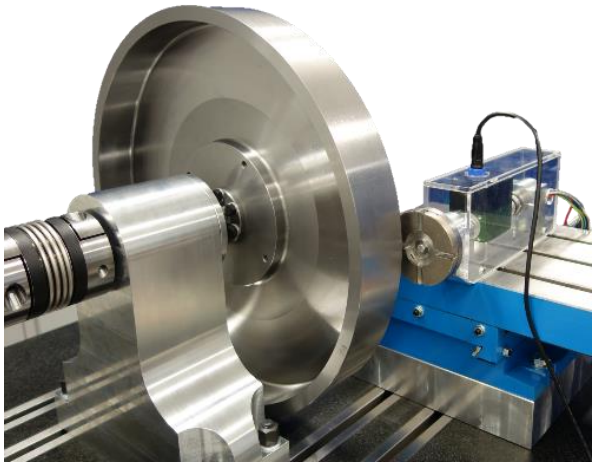
- **A New Concept For Local Energy Harvesting**
  - Non-Contact
  - Modular
  - Robust
  - Self-starting

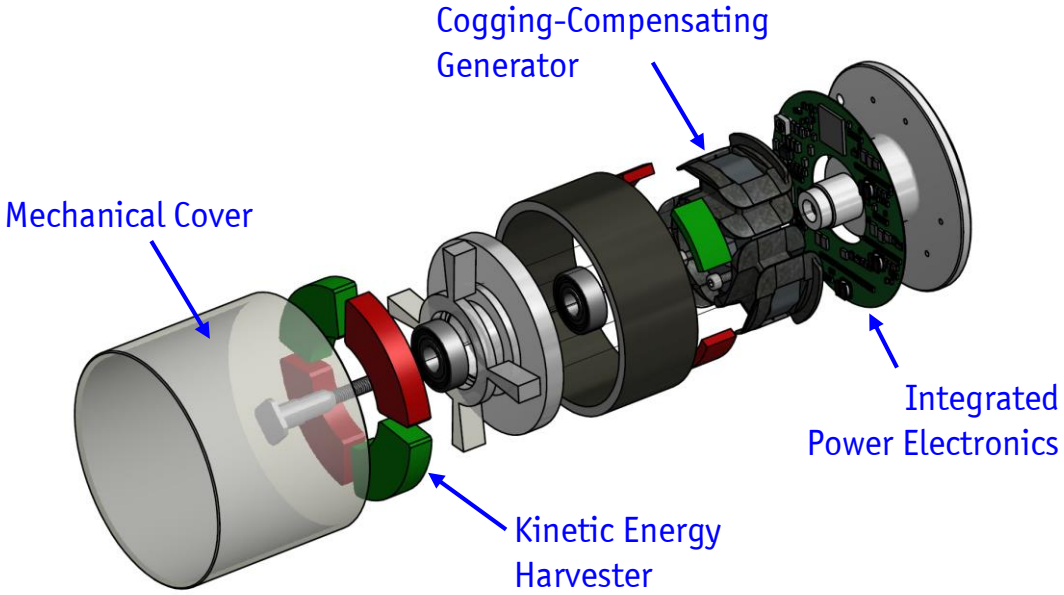


► Energy Harvesting in Railway Applications (2)

■ Optimization for Scaled Test Setups

- Energy Harvester
- Permanent-Magnet Speed Sensors





▶ Advanced Motion Control – A Solution Platform

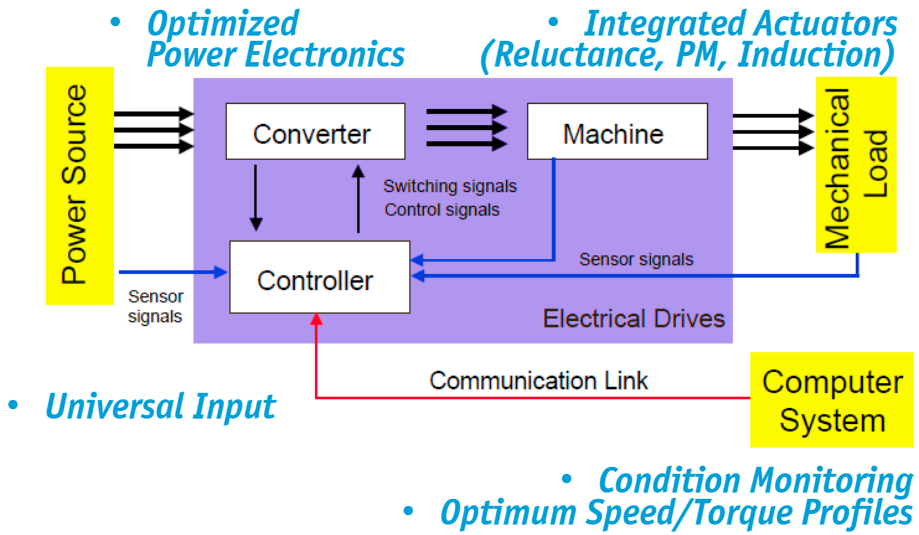
■ Base Technology Package

- Inverter Topology Selection/ Dimensioning
- Modular Control Firmware
- Thermal and Mechanical Integration

- Volume/Weight Reduction
- Cost Reduction
- Hardware in the Loop Verification

■ Key Competence Across Industries

- Railway
- Aircraft
- Commercial Vehicle
- ...



Advanced Mechatronics

The Day After Tomorrow

Medical Applications
Future Mobility
Digitalization / Internet of Things

Advanced Mechatronics

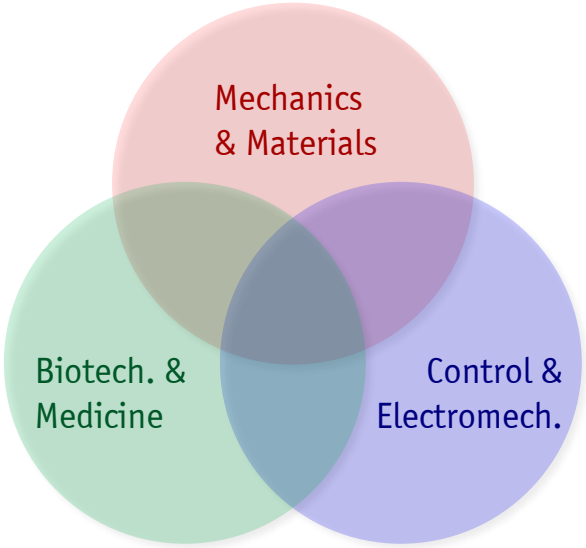
The Day After Tomorrow

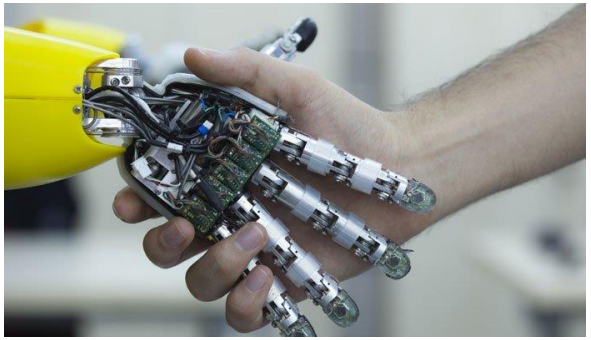
Medical Applications

▶ Paradigm Shift in Healthcare – Biomechatronics

■ **Future of Medical Technology (Future *MegaTrend* in the Developed World)**

- Personalized/Smart Medicine
- Drug Delivery Robots
- Implantable Mechatronics
- Assisted Surgery/Robot Surgeons



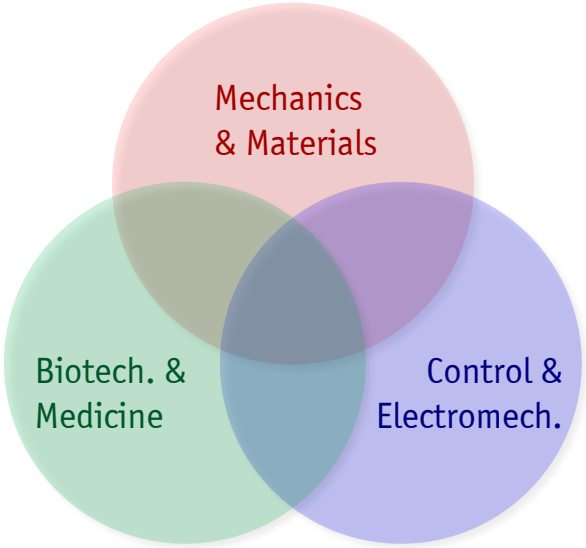


■ **Novel, Interdisciplinary Approaches are Needed**

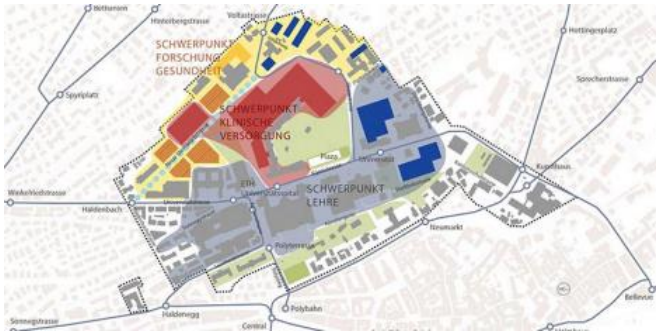
→ **New Competence Centers in Leading Universities**

▶ Paradigm Shift in Healthcare – Biomechatronics

- **New Competence Centers in Leading Universities**
- **ETH Zurich + University of Zurich + University Hospital**
  - Major Infrastructure Planning
  - Medical Competence Center
  - Natural sciences, engineering and medical sciences



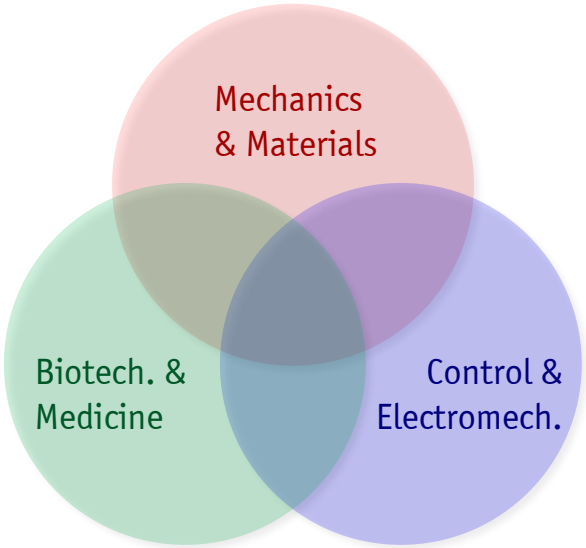
University District of Zurich Today



New Zurich Centre for University Medicine

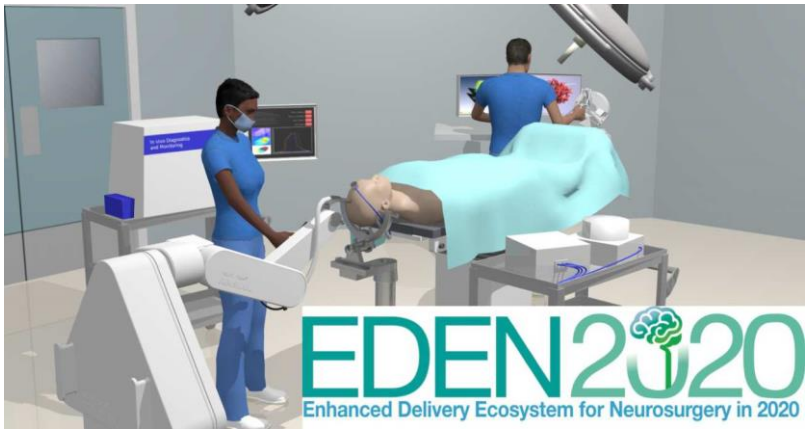
▶ Paradigm Shift in Healthcare – Biomechatronics

■ **New Competence Centers in Leading Universities**



■ **Enhanced Delivery Ecosystem for Neurosurgery**

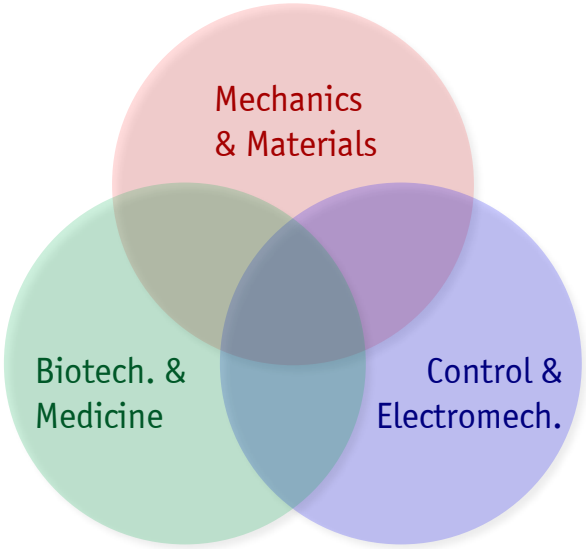
- Robotic-Assisted neurosurgical drug delivery
- EU Horizon 2020 Funding: € 8'300'000



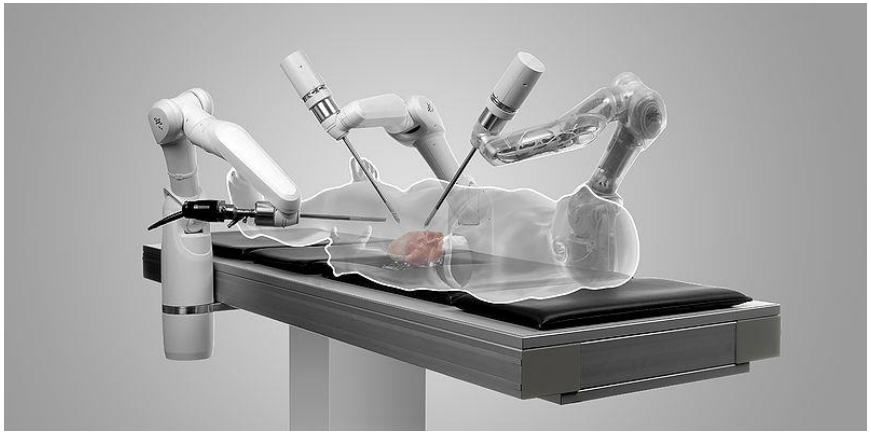
- Imperial College London
- Universita' di Milano
- Politecnico di Milano
- Technical University of Munich
- Universitair Medisch Centrum Groningen

▶ Paradigm Shift in Healthcare – Biomechatronics

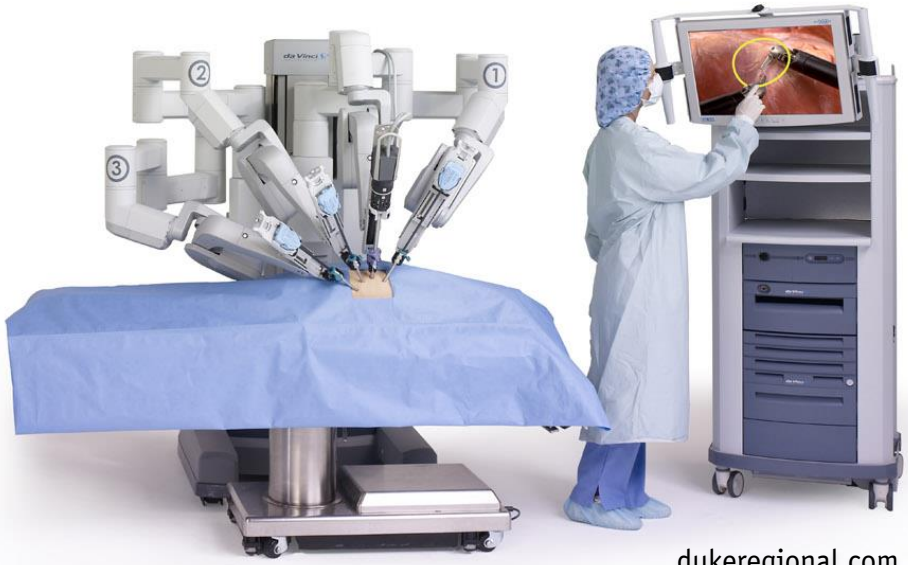
- New Competence Centers in Leading Universities



- Stanford University Bio-X Laboratory
- Stanford University ChEM-H Laboratory
- MIT Biomechatronics Group
- ...



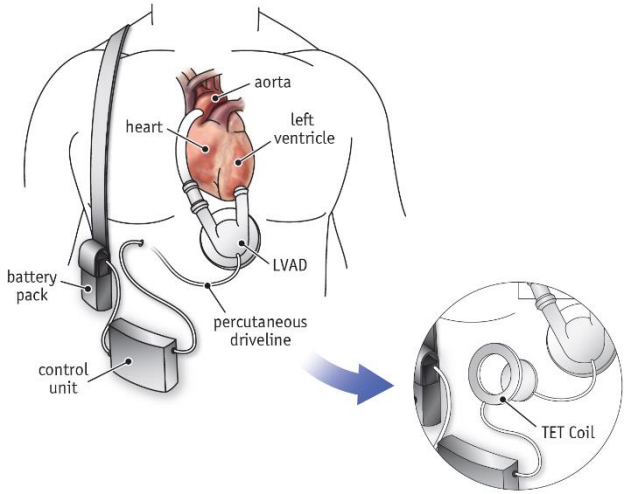
▶ Robotically Assisted Surgical Systems



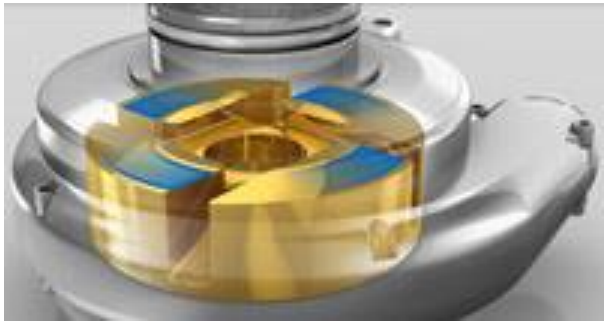
- Four Robotic Arms Holding a Camera and Surgical Instruments
- Complex Procedures with Minimum Invasion due to Small Incisions
- Quicker Recovery Time and Shorter Hospital Stay

► Implantable Left-Ventricular Assist Device

- Highly Compact Electrical Drive for Implantable Blood Pump



- Elimination of Ball Bearings for High Purity
- Hydrodynamic Thrust Bearing (Blood as Fluid)
- Passive Magnetic Bearings

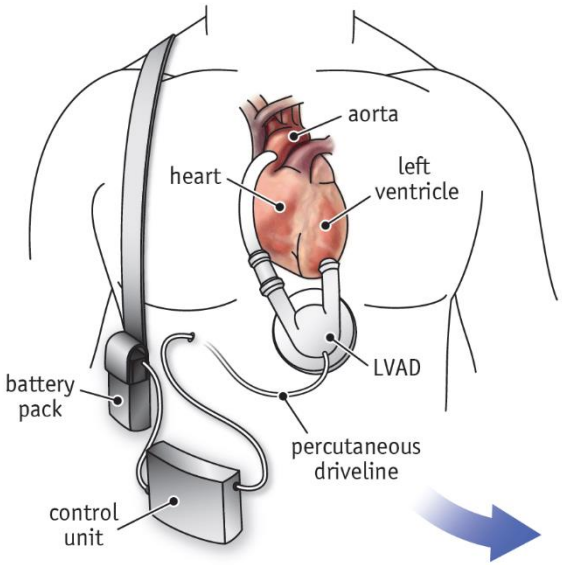


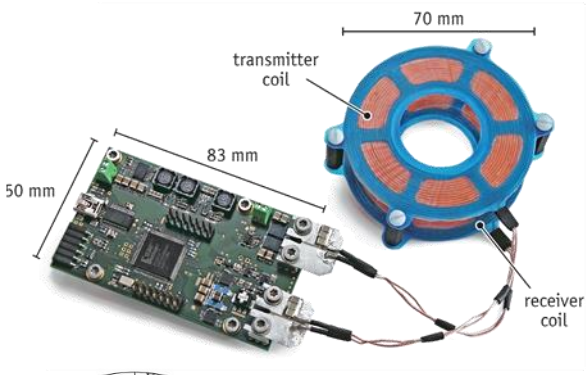
Source: heartware.com

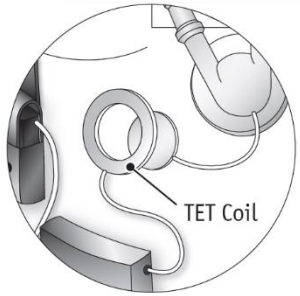
► Transcutaneous Power Supply

- **Implanted Devices with Ever-Higher Energy Demand (e.g. Heart-Assist Devices)**
  - High Risk of Severe Infections due to Conductive Connection

- **Fully-Implantable LVAD**
  - Wireless Power Transfer
  - Wireless Communication
  - Implated Battery Backup
  - Implanted Motor Inverter & Electrical Blood Pump







► **Zurich Heart Project:**

ETH zürich

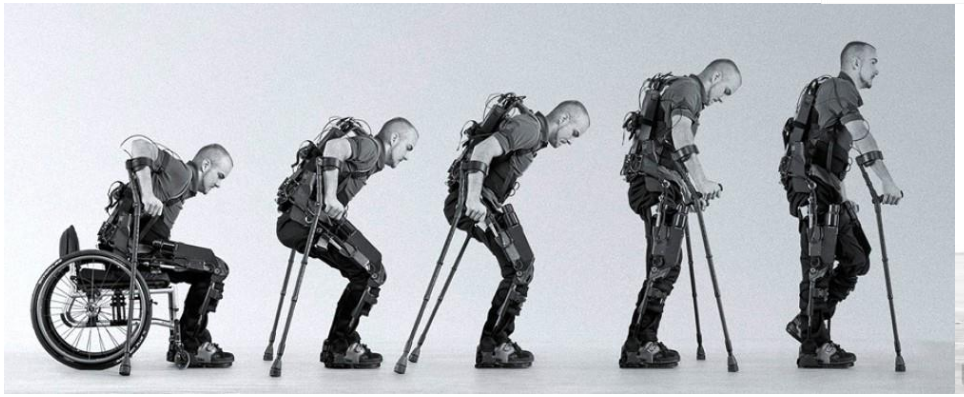
University of Zurich[UZH]

UniversityHospital Zurich

▶ Robotic Exoskeleton for Humans

- Helping Patients with Partial Paralysis or for Rehabilitation After Injury
- Assist Workers with Heavy Lifting or Other Manual Tasks
- Protection of Firefighters/Soldiers in Harsh Environments

ekso BIONICS

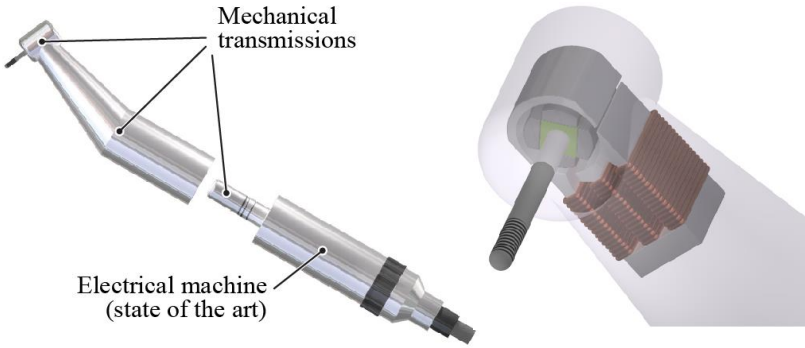


► Integrated Actuator Concepts for Medical Devices

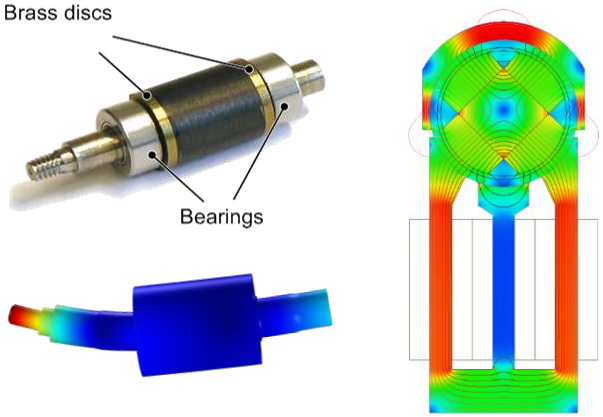
■ Optimization of Machine Design for Application Specific Requirements

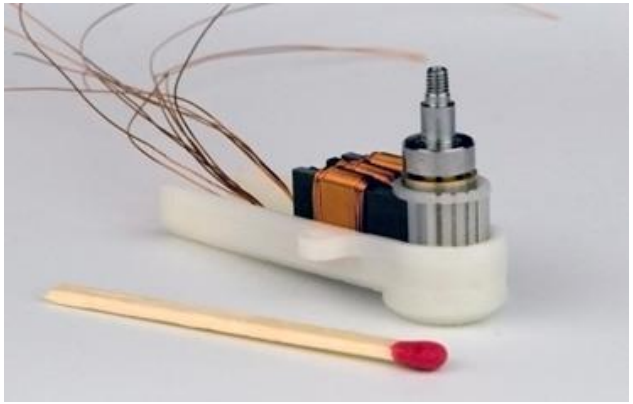
■ Lateral-Stator Machine Concept

- Novel Actuator Topology
- Direct Drive
- 3 x Higher Local Torque Density



■ 2/3-D Numeric Analysis and Optimization





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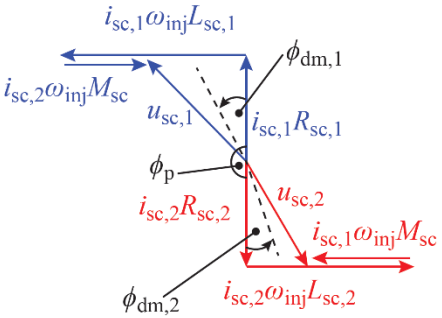
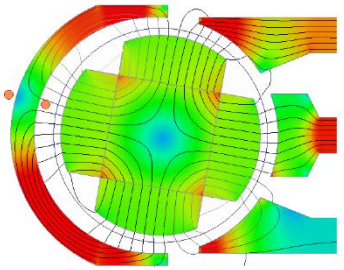
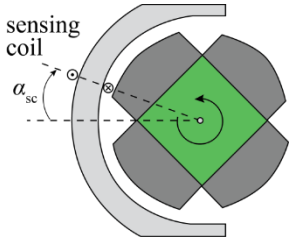
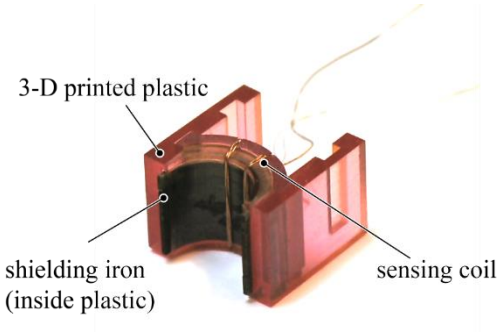


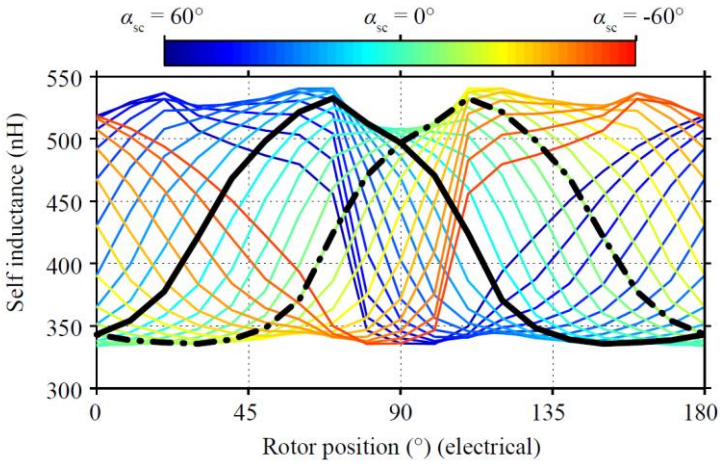


■ Topology-Specific Integrated Position Sensor

- Compact Realization
- Load Independent







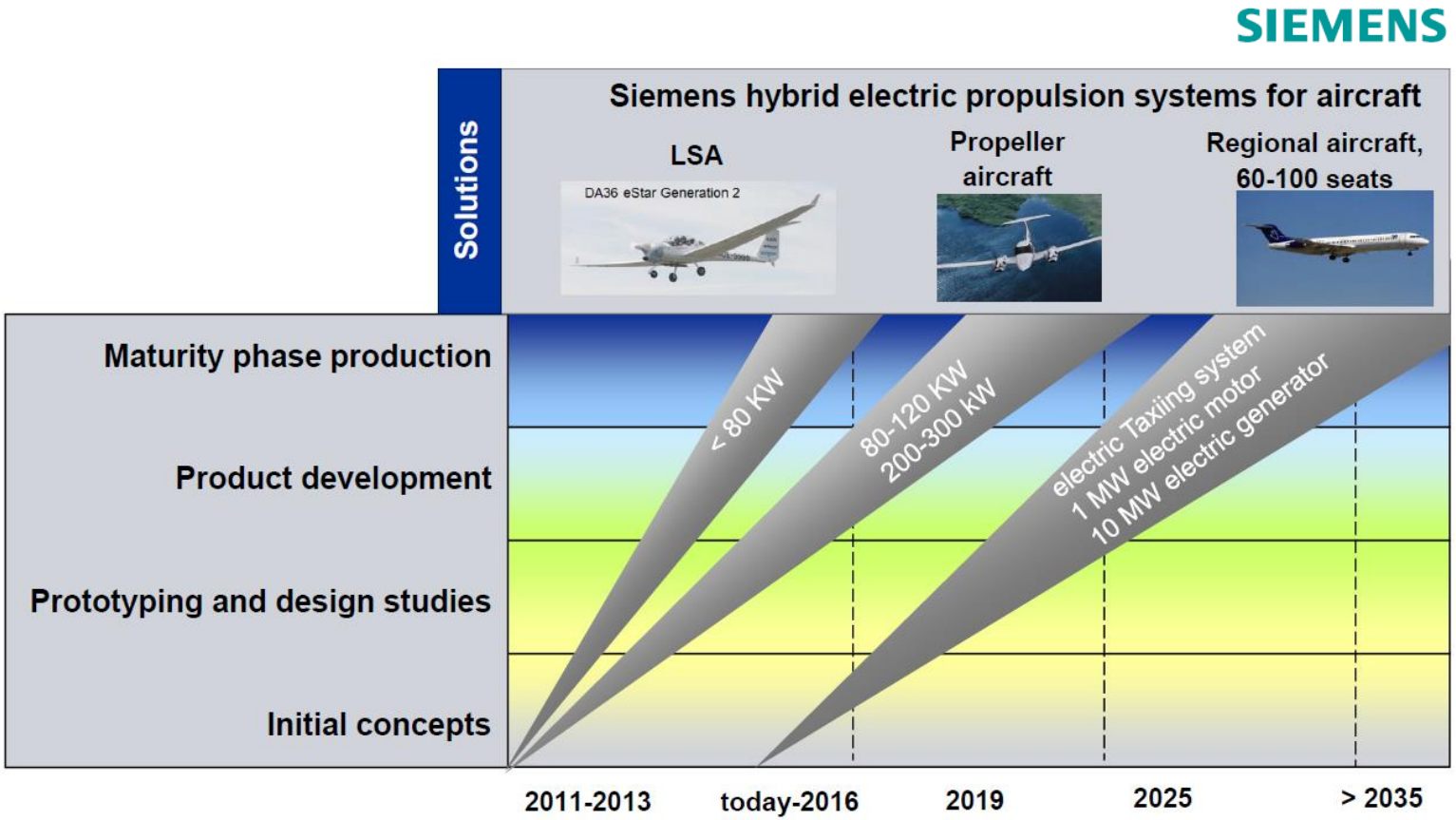
Advanced Mechatronics

The Day After Tomorrow

Future Mobility

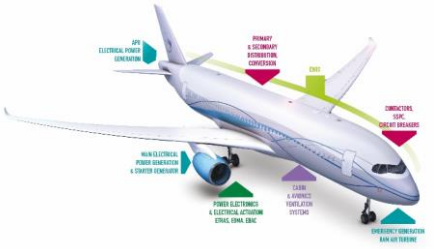
► Future of Transportation: Towards the Full Electric Aircraft

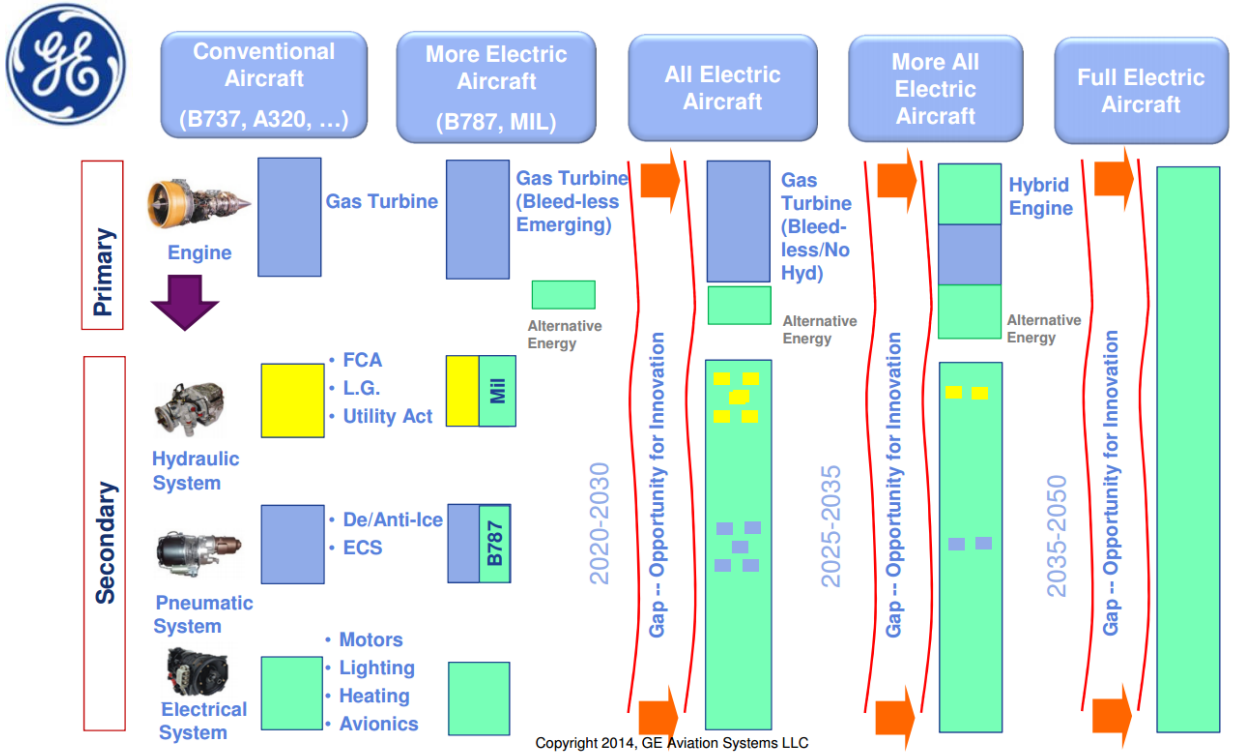
- Today: Full electric 2-seater planes for pilot training
- Near Future: Electric propulsion for regional transportation



► Future of Transportation: Towards the Full Electric Aircraft

- **Reduction of Fuel Consumption and CO_2-Footprint**
  - Lower Noise Emissions and Environmental Impact
- **Multi-Disciplinary Innovation Opportunities!**



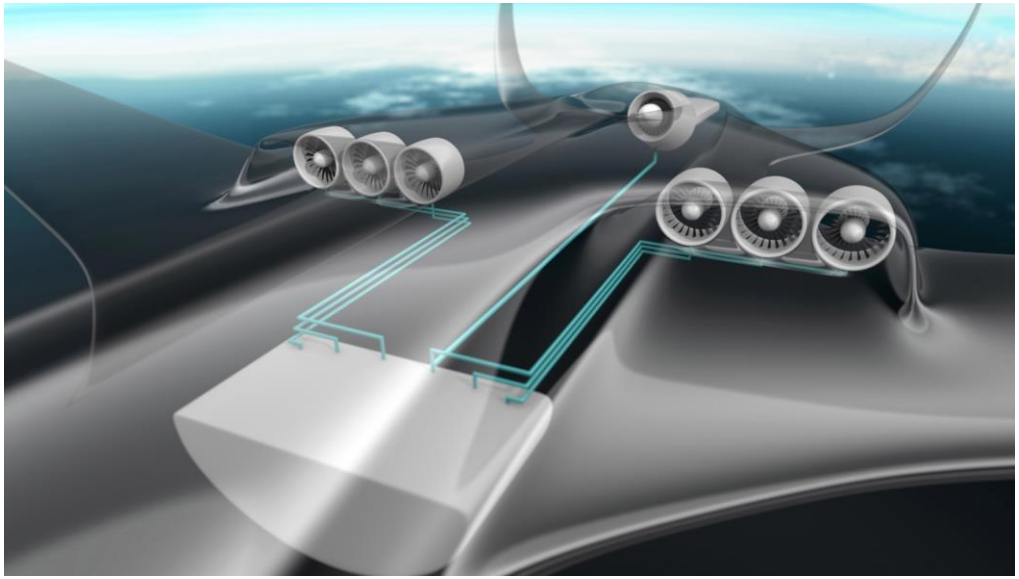


▶ Towards the Full Electric Aircraft

- **Reduction of Fuel Consumption and CO_2-Footprint**
  - Lower Noise Emissions and Environmental Impact

- **Multi-Disciplinary Innovation Opportunities!**

  - Motion Control (Motors, Power El., Control,...)
    +
  - Fuel Cells
  - Batteries
  - Superconductors
  - Composite Materials
  - ...



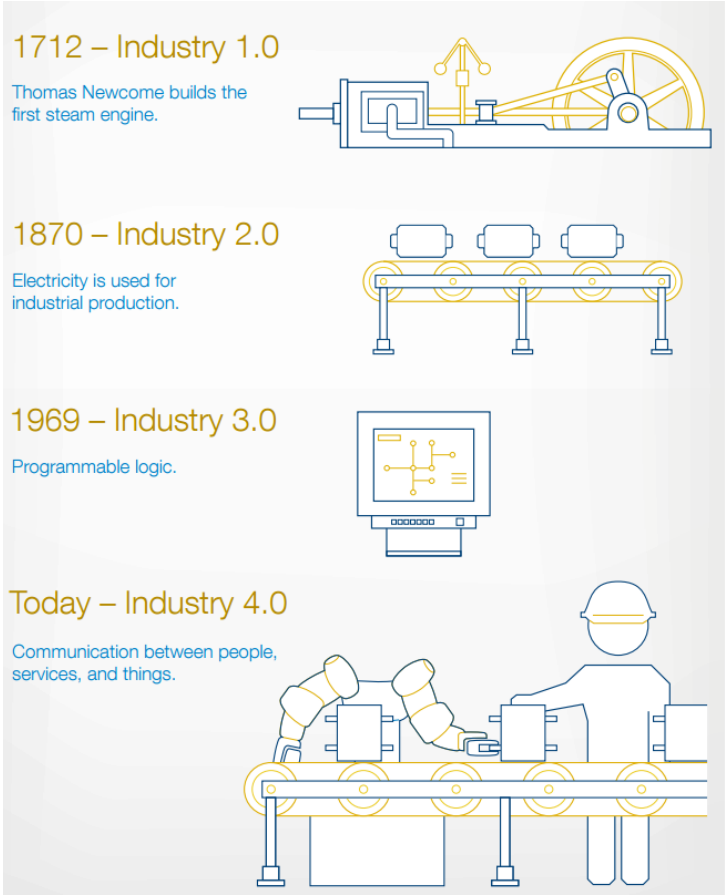
Advanced Mechatronics

The Day After Tomorrow

Digitalization / Internet of Things

▶ Industry 4.0 / Digitalization / Internet of Things

- **Interoperability**
  Devices and people connect and communicate
- **Information Transparency**
  Virtual copy of the physical world
  by increasing the amount of sensors
- **Technical Assistance**
  - Provide humans with comprehensive information
  - Physically support humans by taking over certain tasks
- **Decentralized Decisions**
  Autonomy of cyber-physical systems
  Human input only for exceptions



▶ Industry 4.0 / Digitalization / Internet of Things

- **Condition Monitoring with Add-on Wireless Sensors**
  - Low Investment Cost
  - Vibration, Sounds, Temperature,...
  - Processing of Data in the Cloud
  - Predictive Maintenance
- **High-Fidelity Models**
  - 4-D Simulations of Factories
  - Virtual Commissioning
- **Remote Support**
  - Expert Data Analysis
  - Higher Productivity
  - Enhancing reliability

▶ Industry 4.0 / Digitalization / Internet of Things

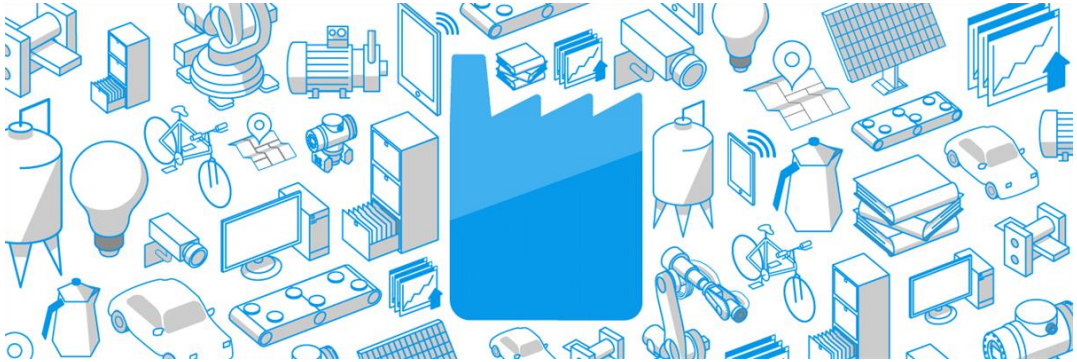
■ Disruptive Changes in Industries, Markets, and Global Economy

ABB appoints Guido Jouret as Chief Digital Officer

Internet of Things pioneer to drive next level of ABB's digital solutions

Zurich, Switzerland, September 5, 2016 – ABB has appointed Guido Jouret, a pioneer of the Internet of Things, as Chief Digital Officer, reporting to ABB's CEO Ulrich Spiesshofer, effective October 1, 2016. Jouret will lead the next level of development and deployment of ABB's digital solutions for customers globally and across all businesses.

ABB



Conclusions

▶ Summary

Future Perspectives for Mechatronics

▶ **Possible Ways for *«Component»* and *«System»* Performance Improvement**

- Miniaturization
- Application Specific Design
- Integrated Design
- Systemization (Converter, Actuator, Sensor, Storage, …)
- …

▶ **Future High-Performance *«Smart»* Systems**

- Healthcare & Medical Systems
- Mobility on Land/Air/Sea
- Digitalization / Internet of Things
- …

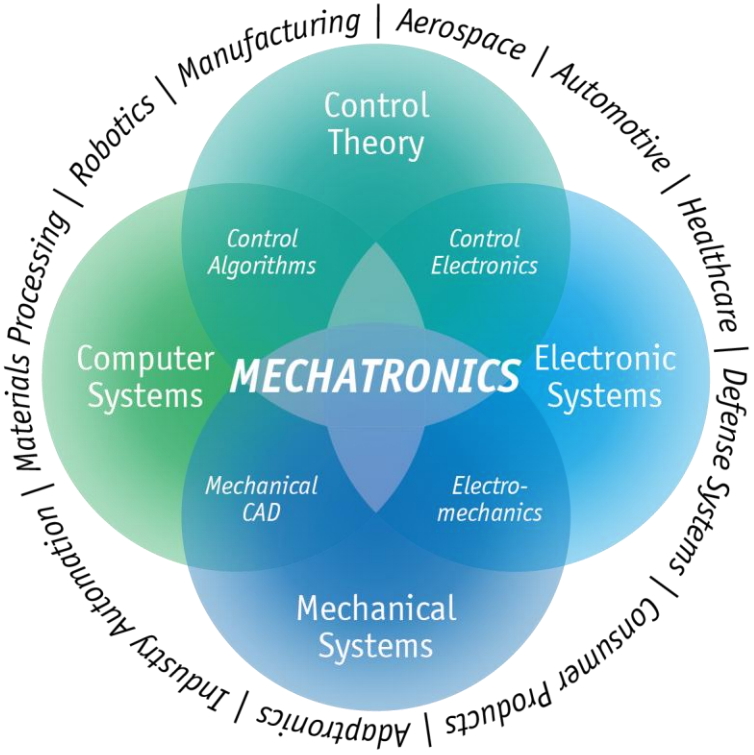
▶ Smart Mechatronic Systems

■ Cover Core Competences in Mechatronic Areas

- Interdisciplinary Engineering Knowledge
- Application-Specific Combination of High-Performance Components

- Characteristics
  → ***Smart***
  → ***Integrated***
  → ***Hybrid***
  → ***Ubiquitous***

- Future
  → ***Automatization (Machine Learning)***
  → ***Modularization***
  → ***Internet of Things, Services, People***



▶ Endless Product Innovation Possible by Combination of Core Elements

Bounded only by

- **Laws of Physics**
- **Material Properties**
- **Imagination / Vision**

«Multiplication by Infinity»

Thank You!

Questions?