Introduction to Robotics

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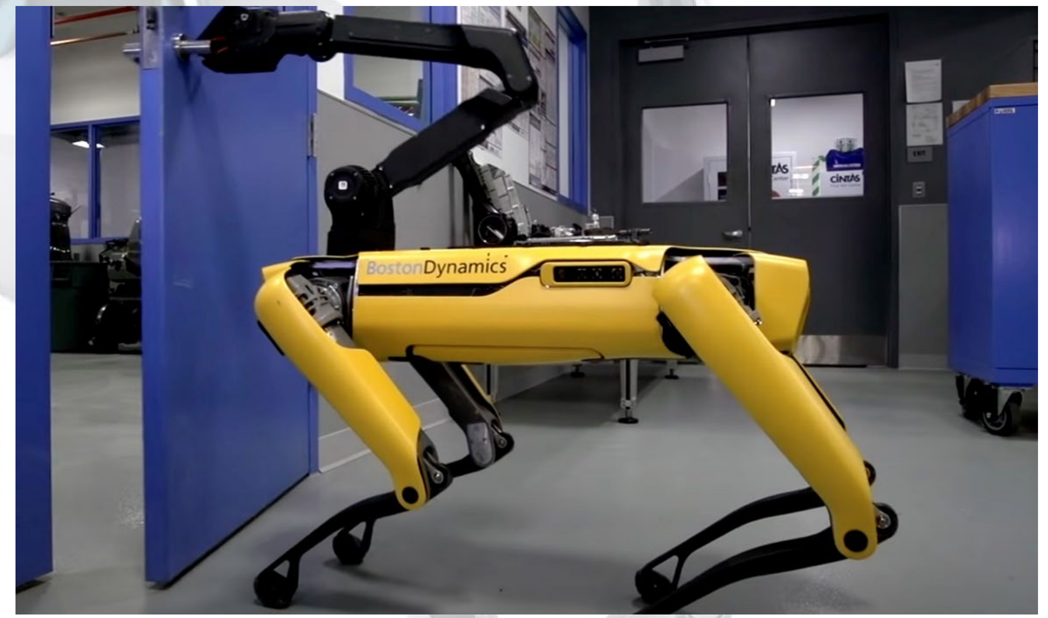
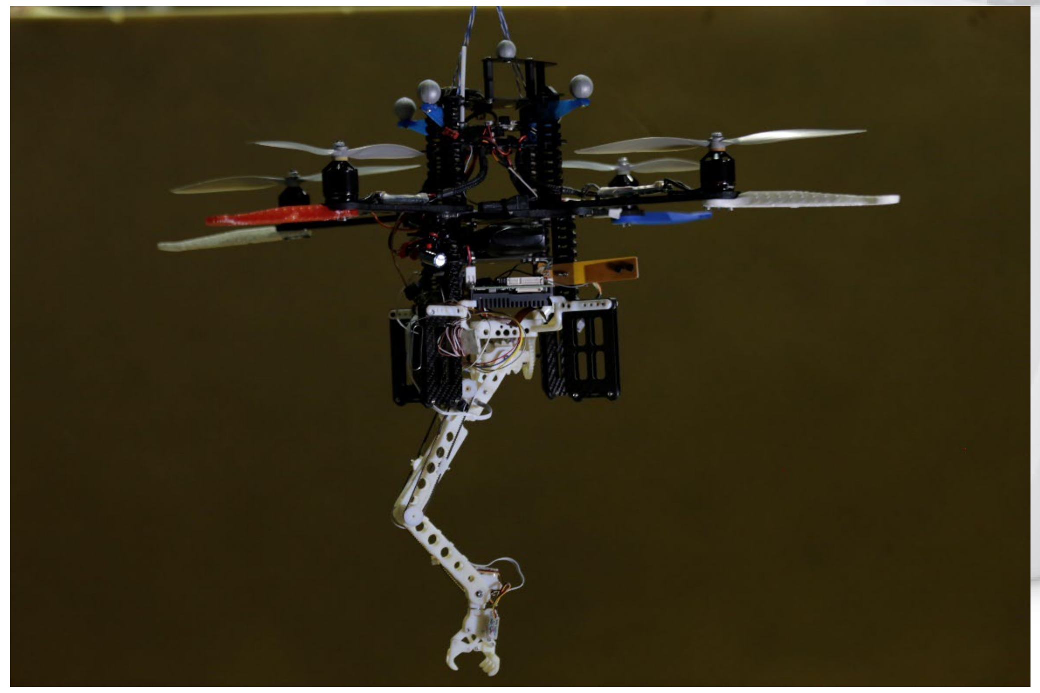
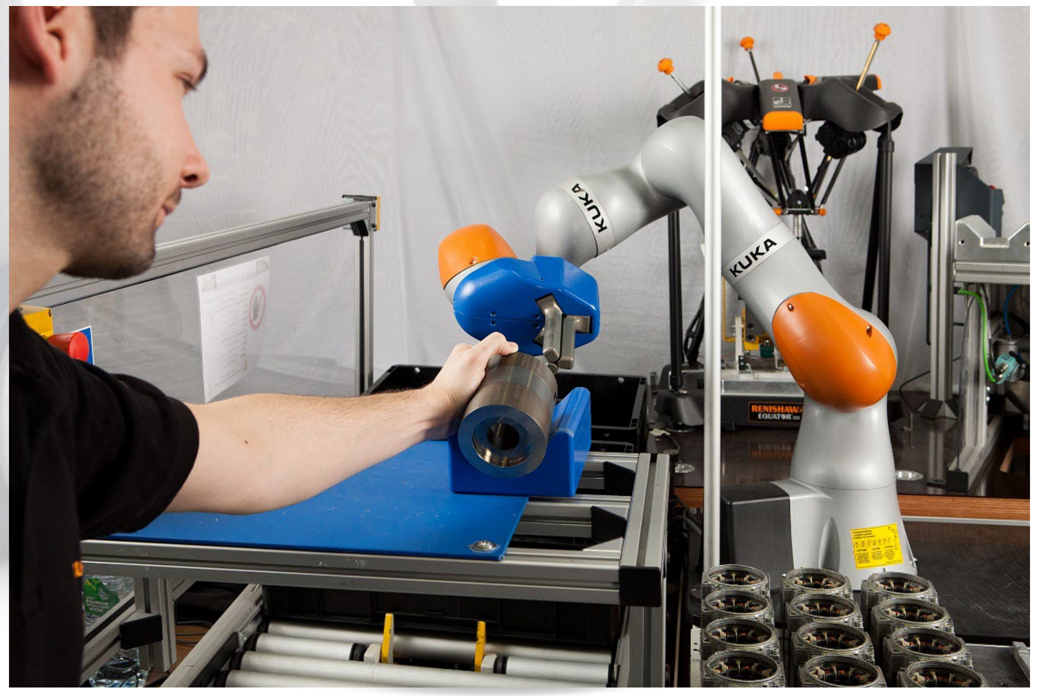
robot

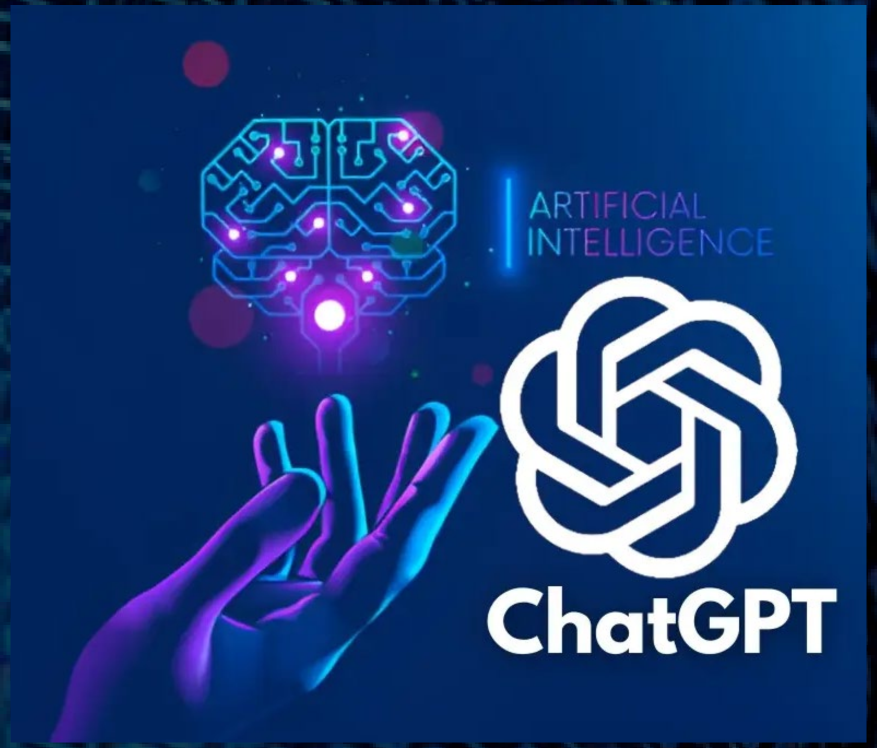






NO robot

IBM Watson



What is a Robot?

Robot (robota = …

One of humans … *tifacts (mythology)*

Common peopl … *can speak, walk, see, and* … *nans (science fiction* …

The robot is see … *s able to execute tasks i* … *bour (reality)*

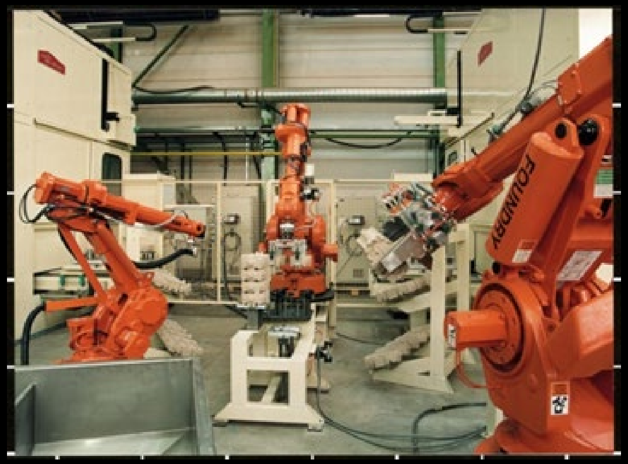
History of Robotics

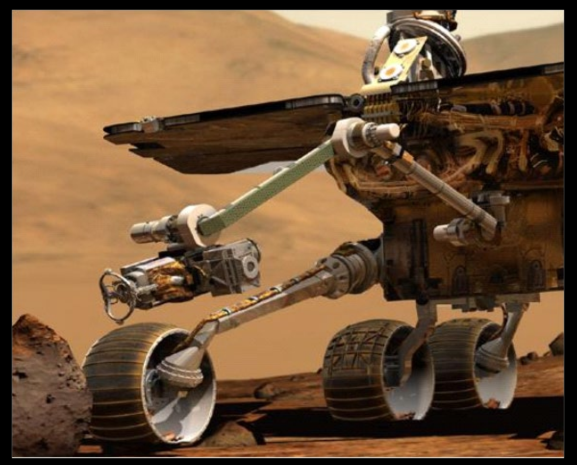
Humans' DREAM of replicating themselves

NEED for useful machines

industrial robotics
1960-1980

manufacturing applications





field robotics
1980-2000

space applications

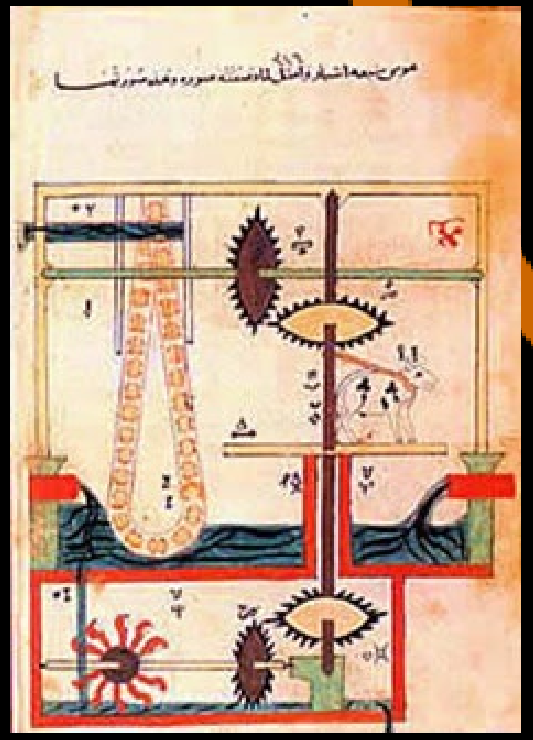
service robotics
2000-2020

medical applications

personal robotics
2020-2040

humanoid robotics

?



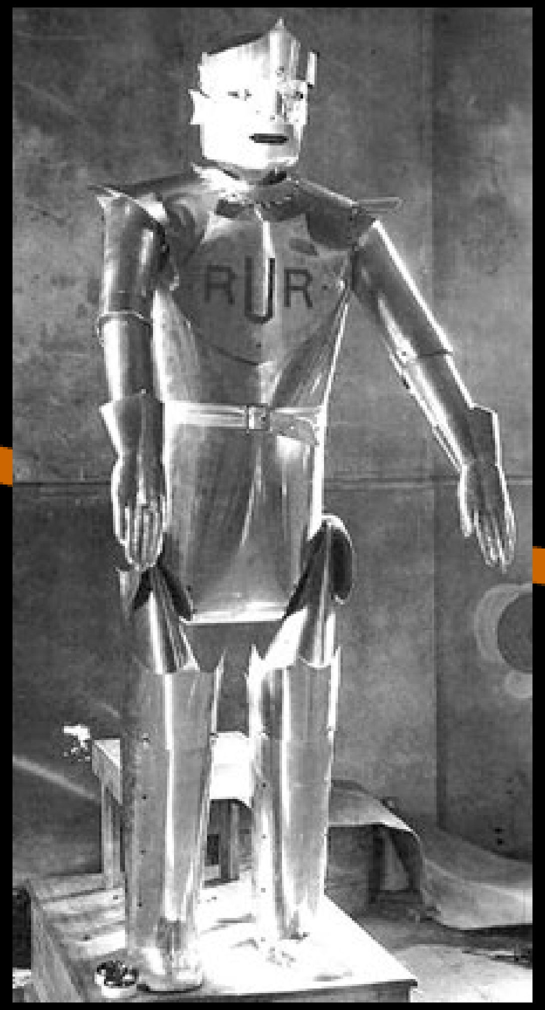
1200

1500

1550

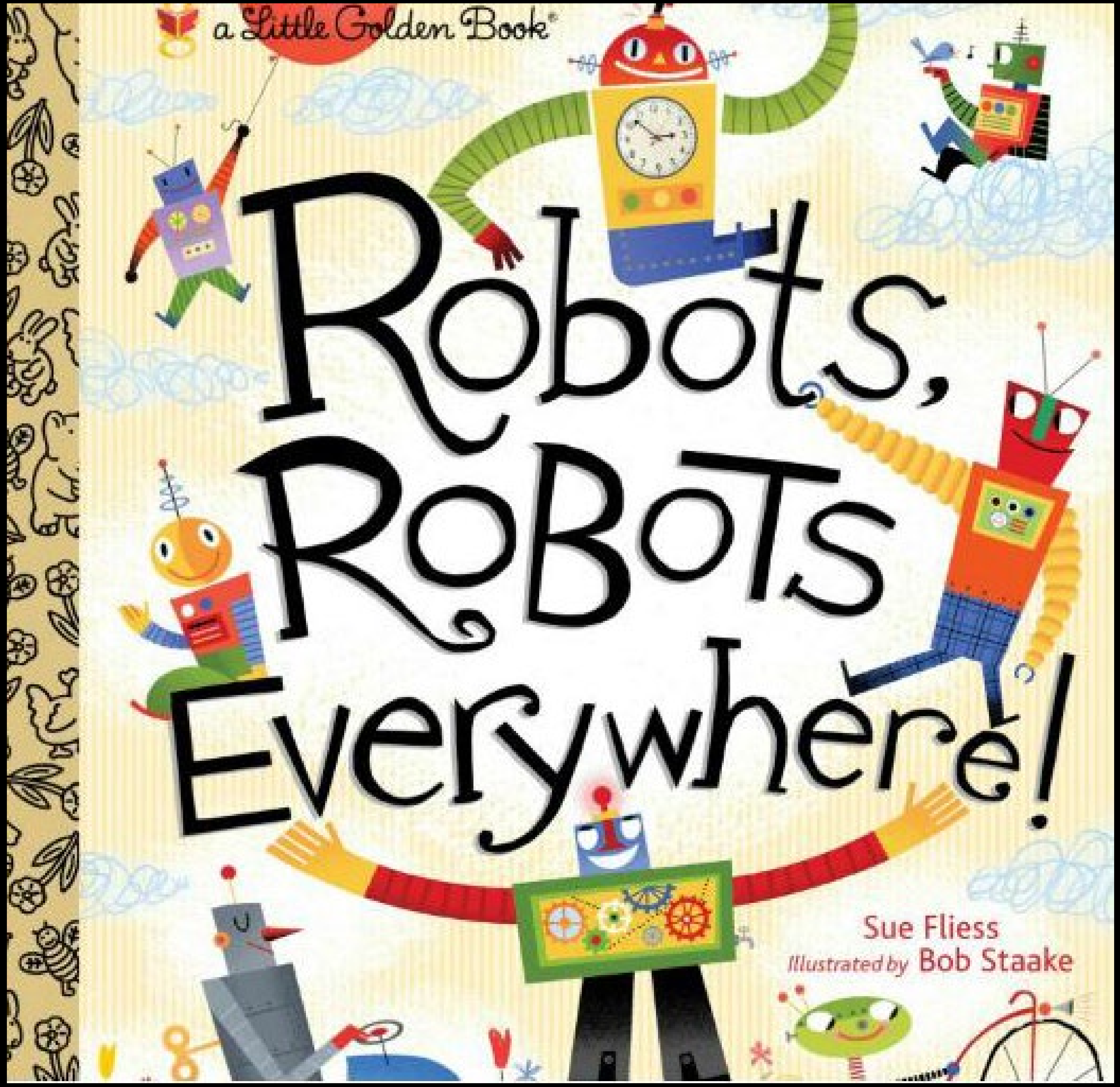
1750

1920



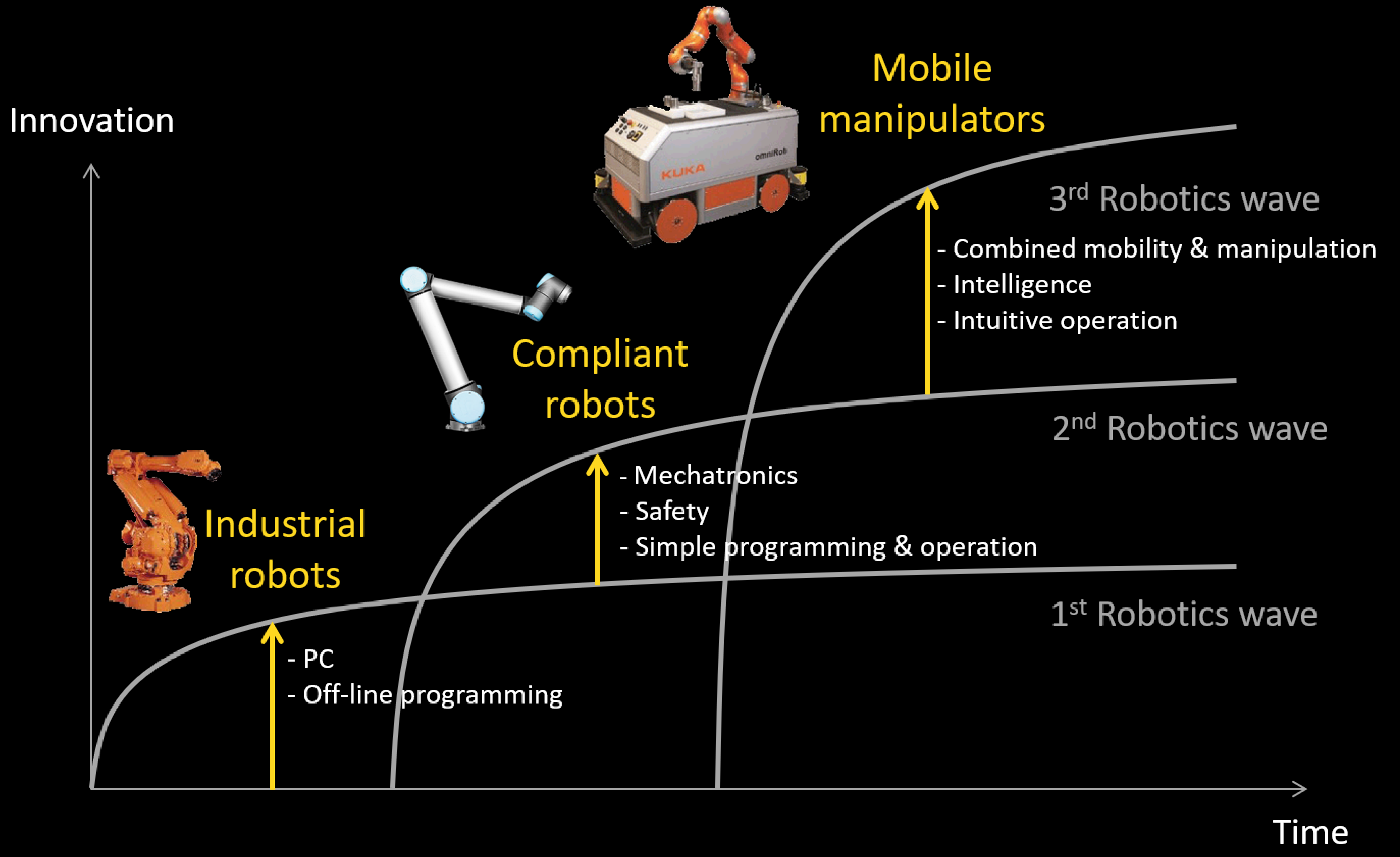
2005

The Age of Robots



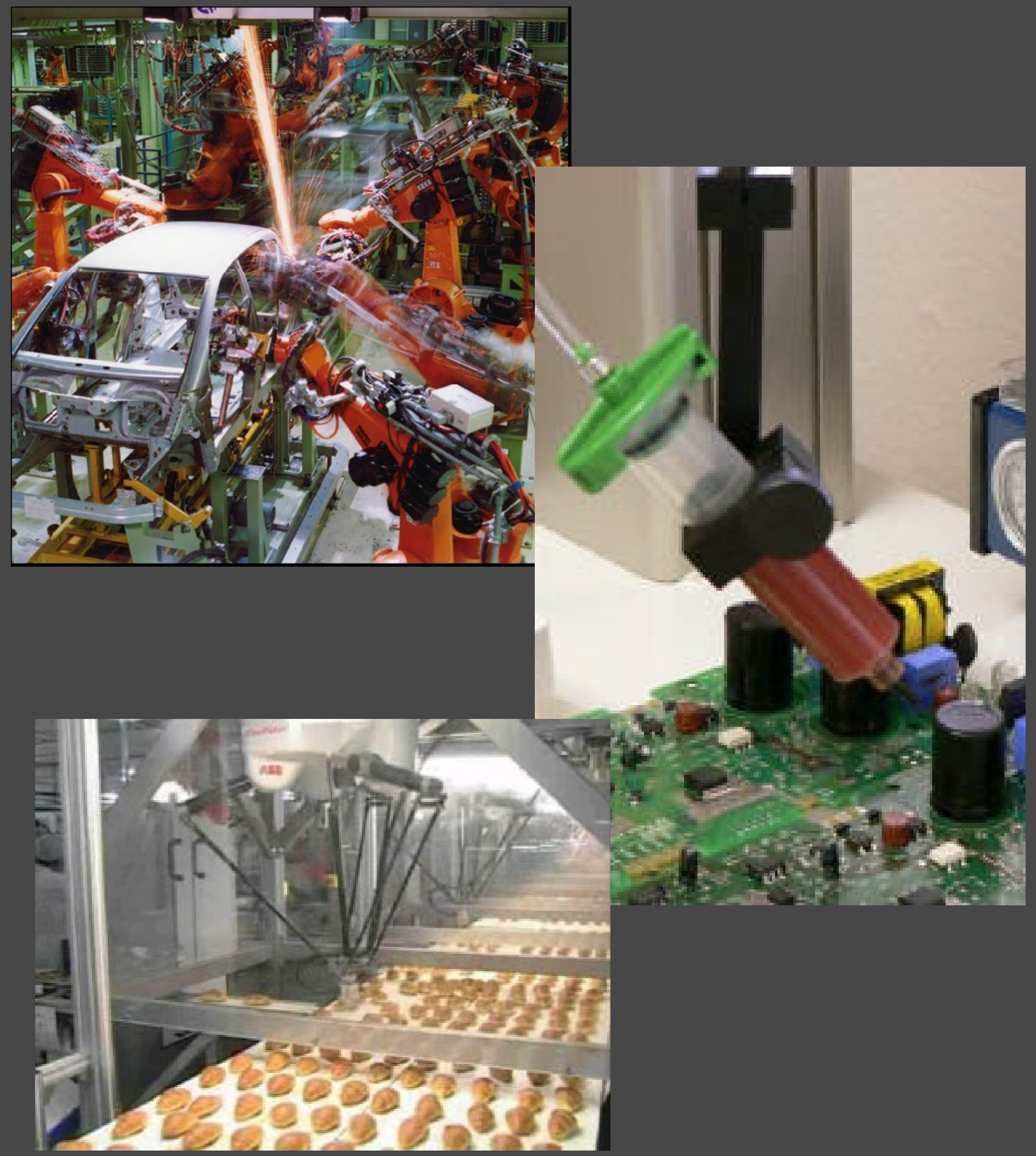

robots are
with us
within us
among us
Photo © Sam Ogden

Industrial Robotics Evolution



Robot Classification

Industrial robots



Used for factory automation (mainly manufacturing): automotive, electrical/electronics, metal & machinery, plastic & chemical, food

Service robots

Perform useful tasks for humans or equipment excluding industrial automation

Professional service robots

Used for commercial tasks by trained operators: cleaning public places, delivery in offices or hospitals, fire-fighting, rehabilitation, surgery

Personal service robots

Used for non-commercial tasks by untrained persons: house cleaning, automated wheelchairs, personal mobility assist robots, pet exercising robots

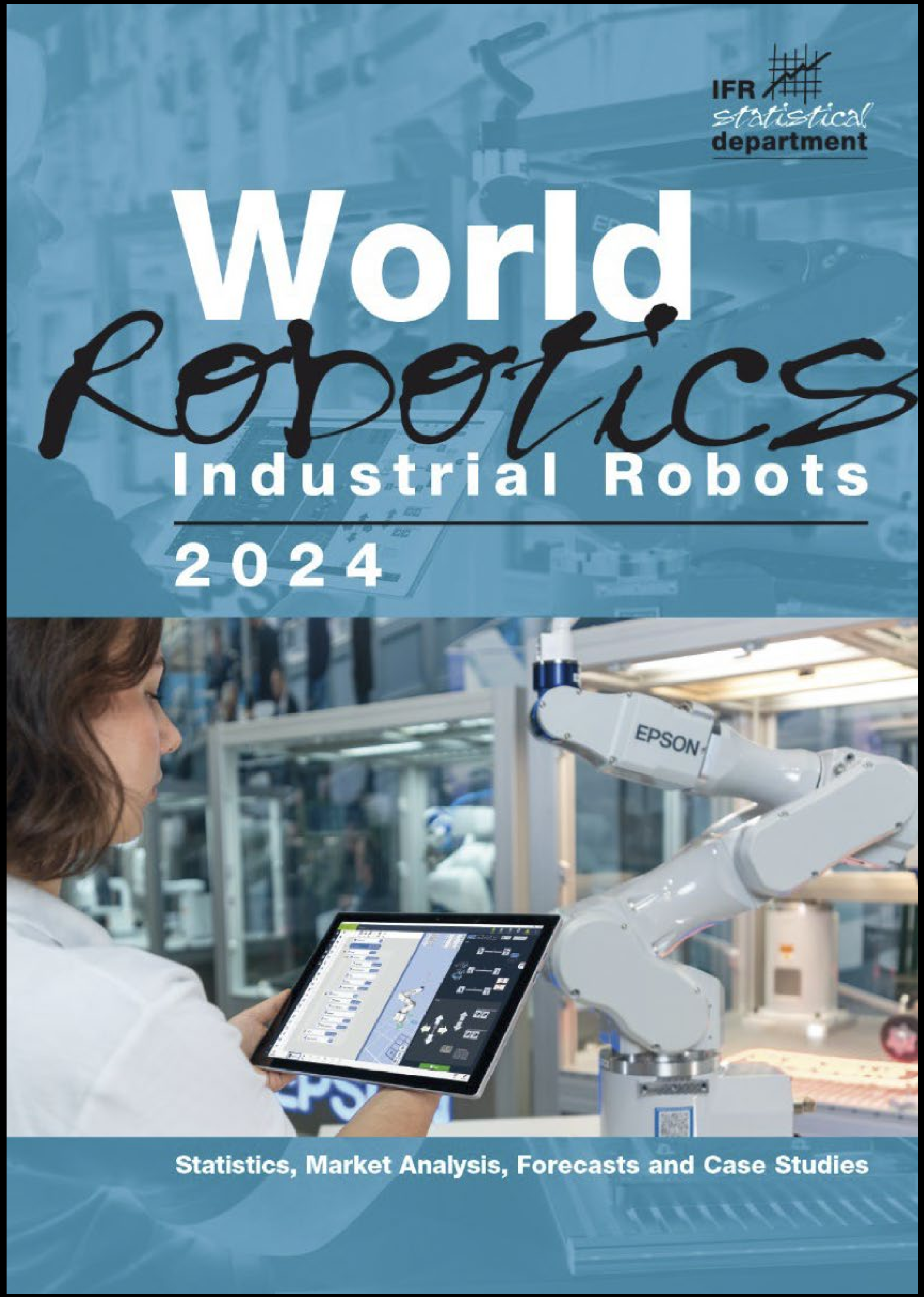
IFR International Federation of Robotics

https://ifr.org

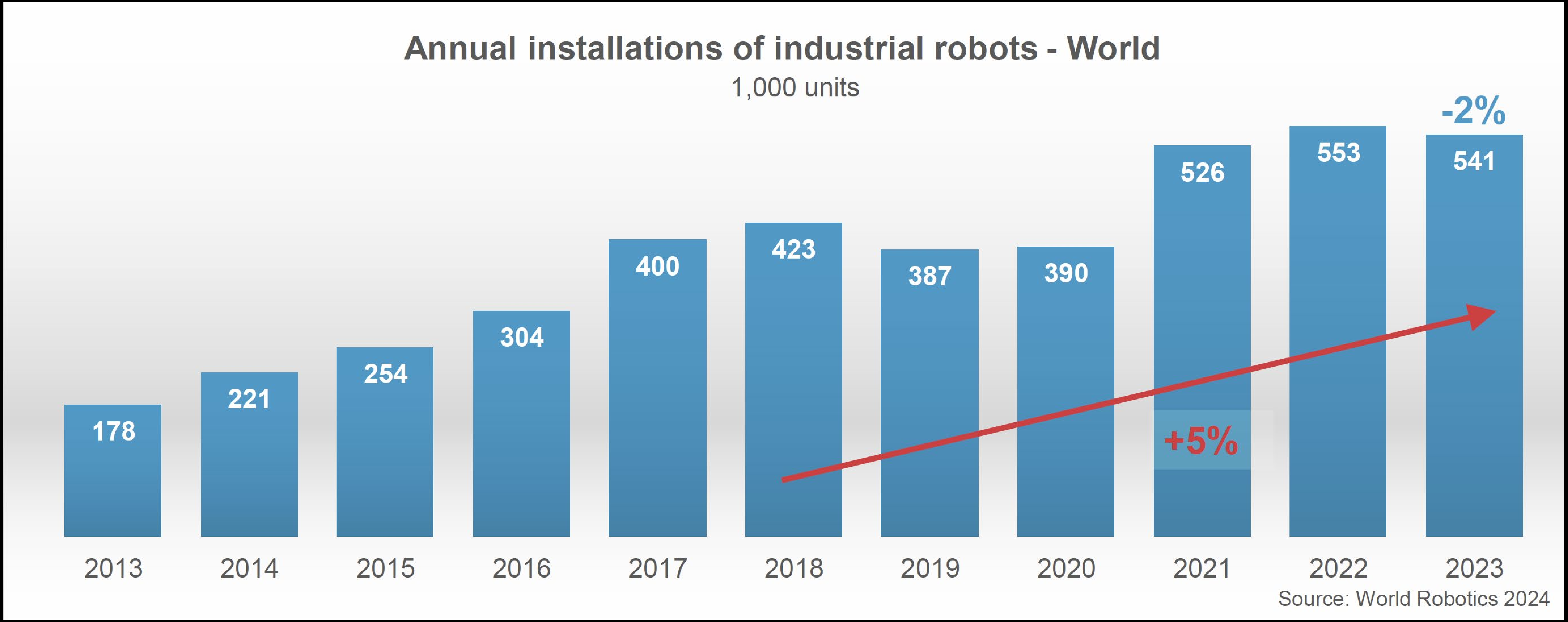
The classification of a robot is done according to its intended application

World Statistics

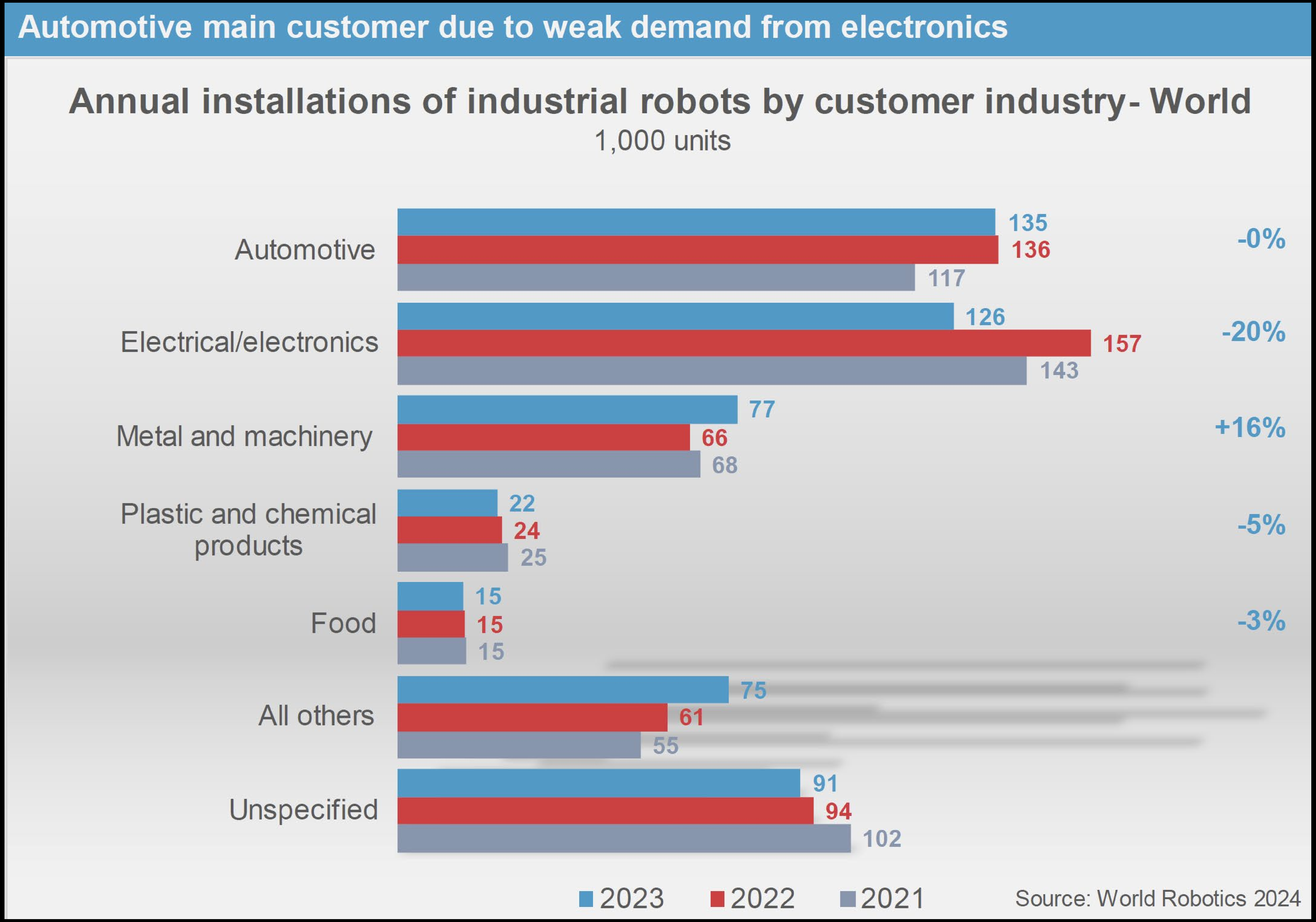
- ✓ *4.3 million of robots @ work worldwide (+10%), CAGR 2018–2023 +12%*
- ✓ *541.000 new installation in 2023 (-2%), CAGR 2018–2023 +5%*
- ✓ *Largest markets: China, Japan, USA, Korea, Germany, Italy (90%)*



Robots At Work



Application Sectors



Technology Trends

- ✓ *Mobile manipulators offer new use cases, whenever transportation and handling tasks need to be jointly automated end-to-end in one device*

- ✓ *Research & development of humanoid robots will yield new technological capabilities*

- ✓ *Improvements in marketable artificial intelligence solutions at an incredible pace*

Market Trends

- ✓ *Labor scarcity in many developed economies is driving the demand for automation*
- ✓ *Reconsideration of supply chains and closeness to customers*
- ✓ *Small and medium sized enterprizes (SMEs) need easy access to automation https://go4robotics.com/*

Service Robots

New professional service robots (incl. AMRs)

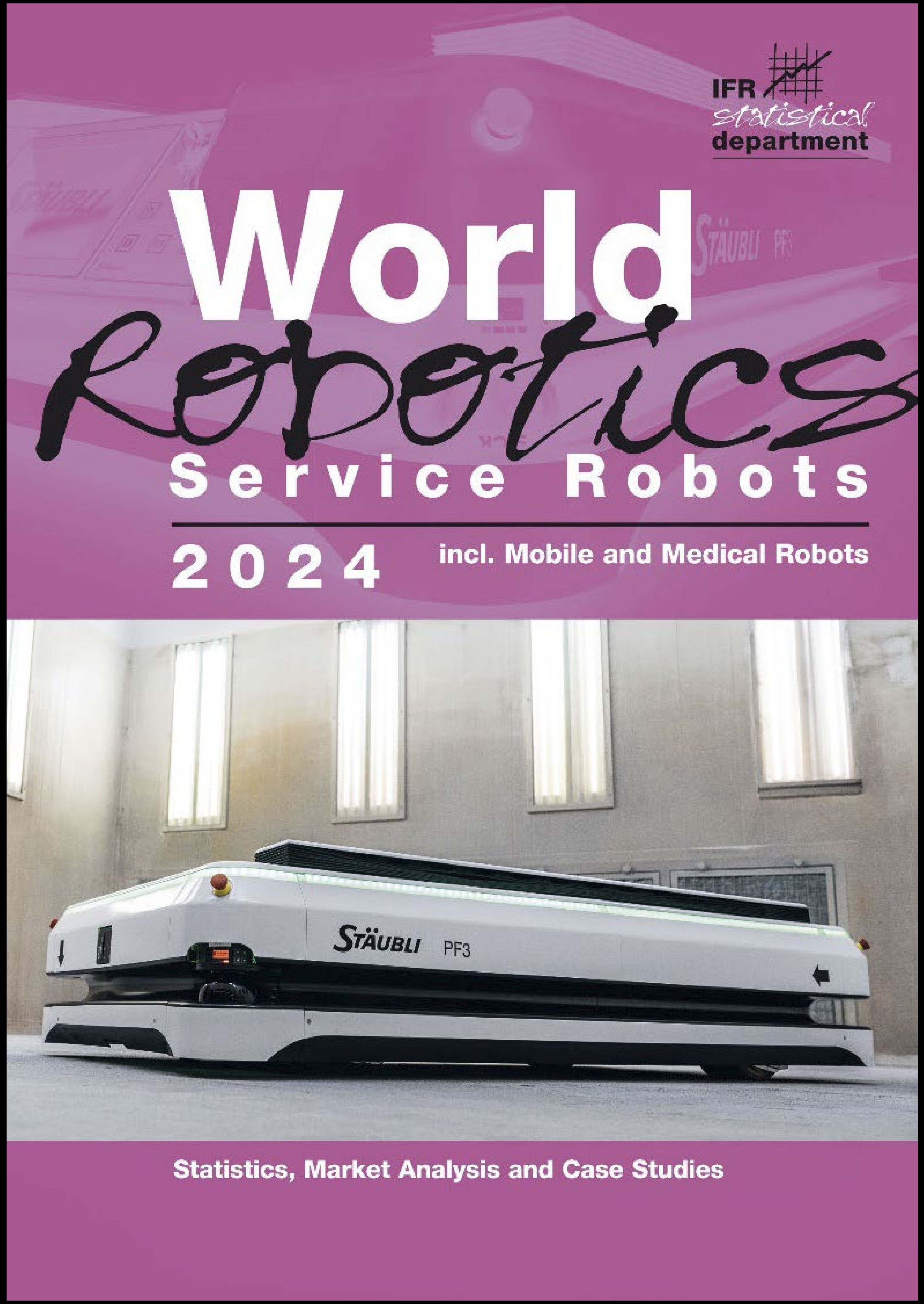
- ✓ *205,000 units (+30%)*

New medical robots

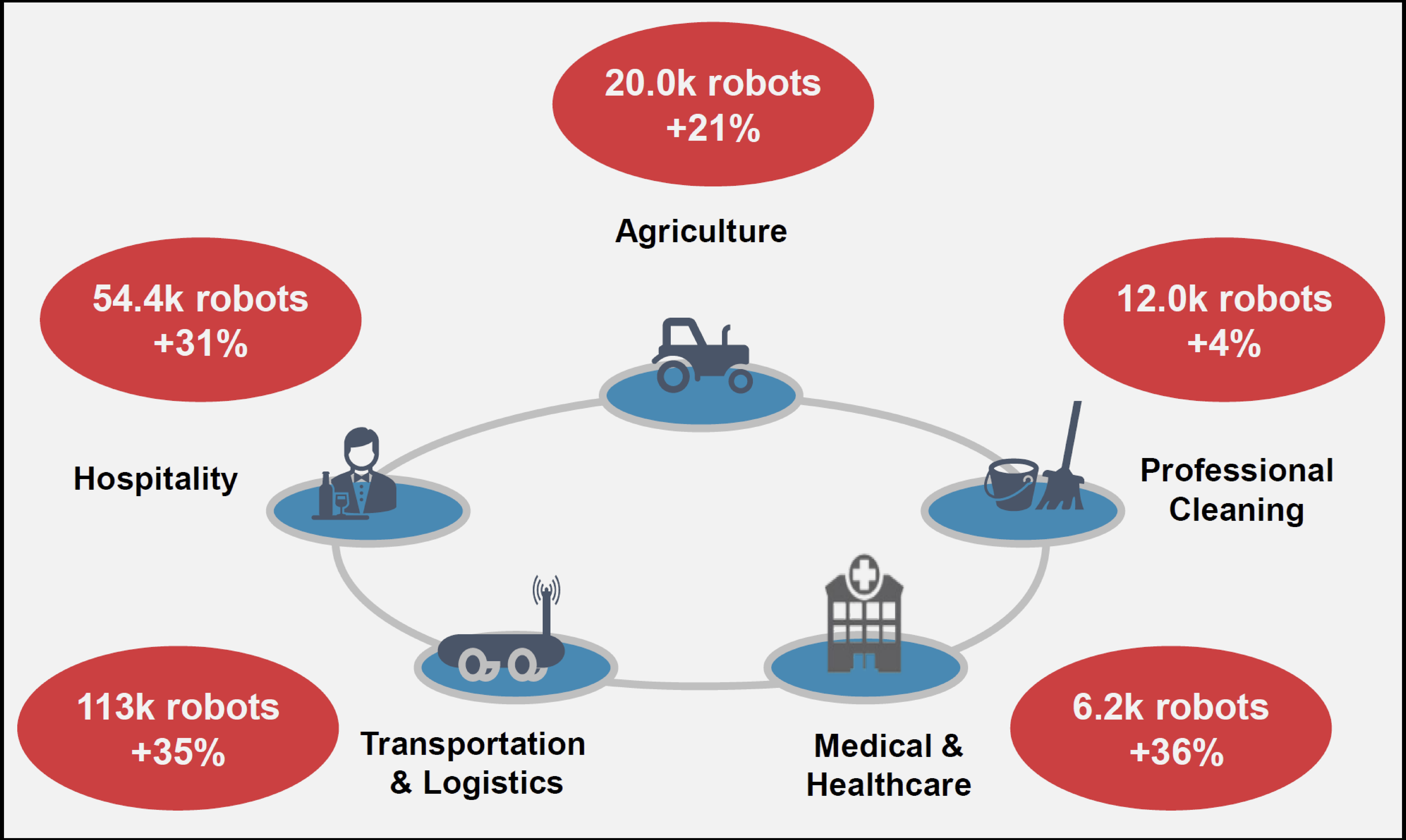
- ✓ *6,200 units (+36%)*

New consumer service robots

- ✓ *4.1 million units (+1%)*



Application Sectors

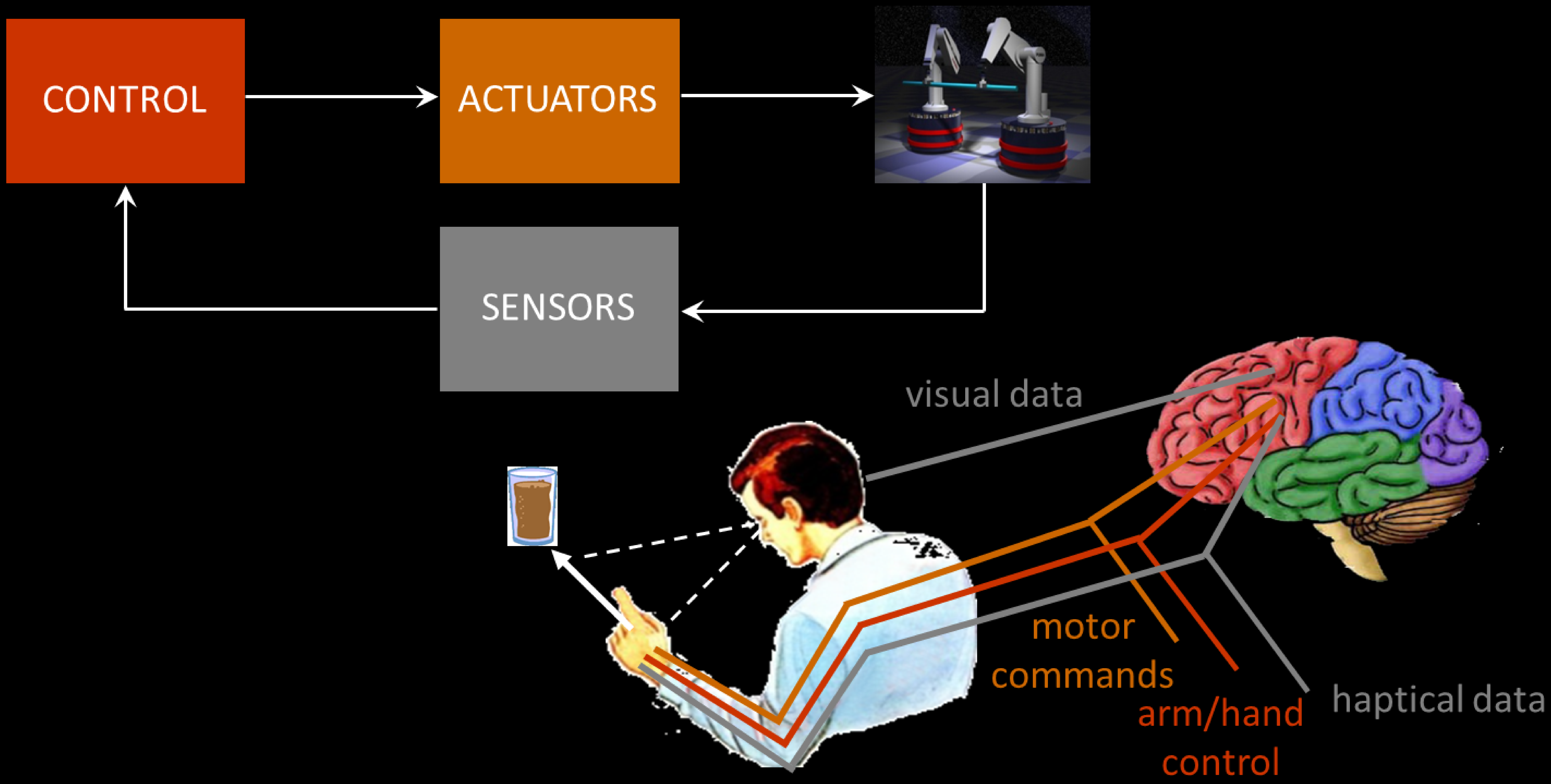


Outlook

- ✓ *Technological advances, e.g. in generative AI, improve robot performance and applicability*
- ✓ *Demographic change: scarcity of labor is driving robot demand*
- ✓ *Need for further standards, e.g. on safety*
- ✓ *Excellent long-term prospects*

Robotics

intelligent connection of perception to action



Components of a Robotic System

Mechanical system

- ✓ *Locomotion apparatus (wheels, crawlers, mechanical legs)*
- ✓ *Manipulation apparatus (mechanical arms, end-effectors, artificial hands)*

Actuation system

- ✓ *Animates the mechanical components of the robot*
- ✓ *Motion control (servomotors, drives, transmissions)*

Sensory system

- ✓ *Proprioceptive sensors (internal information on system)*
- ✓ *Exteroceptive sensors (external information on environment)*

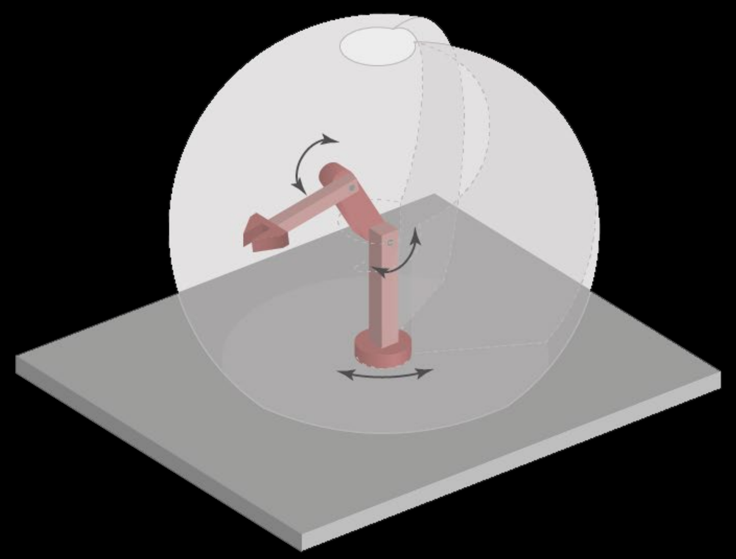
Control system

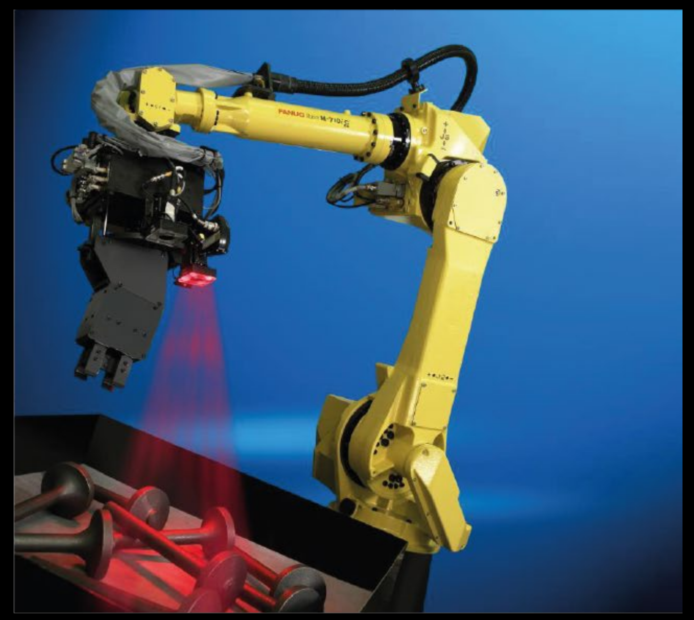
- ✓ *Execution of action set by task planning coping with robot and environment's constraints*
- ✓ *Adoption of feedback principle*
- ✓ *Use of system models*

Robot Manipulators

Mechanical structure of robot manipulator: sequence of rigid bodies (links) interconnected by means of articulations (joints)

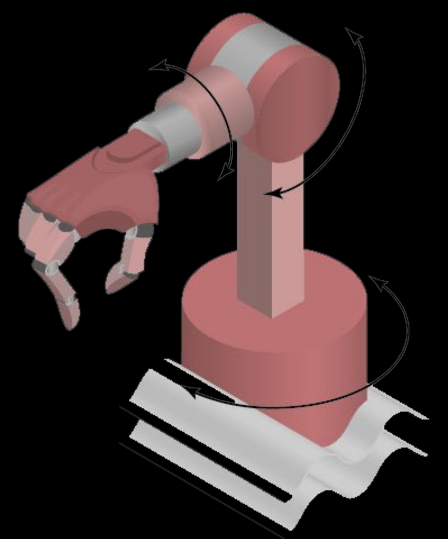
- ✓ *Arm ensuring mobility*
- ✓ *Wrist conferring dexterity*
- ✓ *End-effector performing the task required of robot*

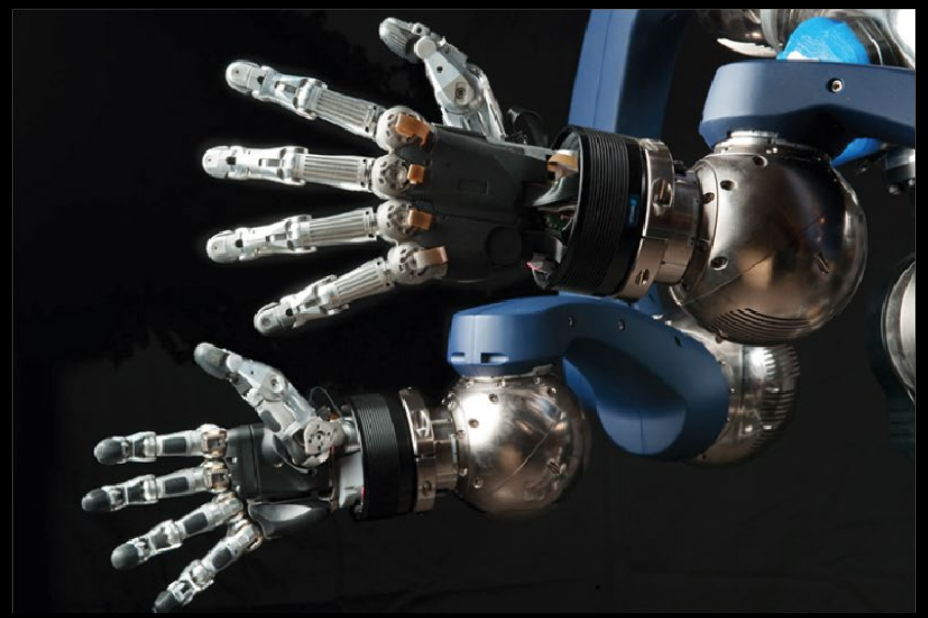


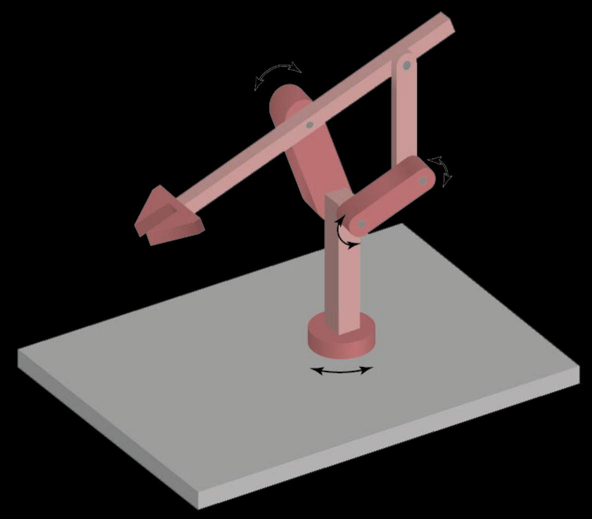


Mechanical structure

- ✓ *Open vs. closed kinematic chain*





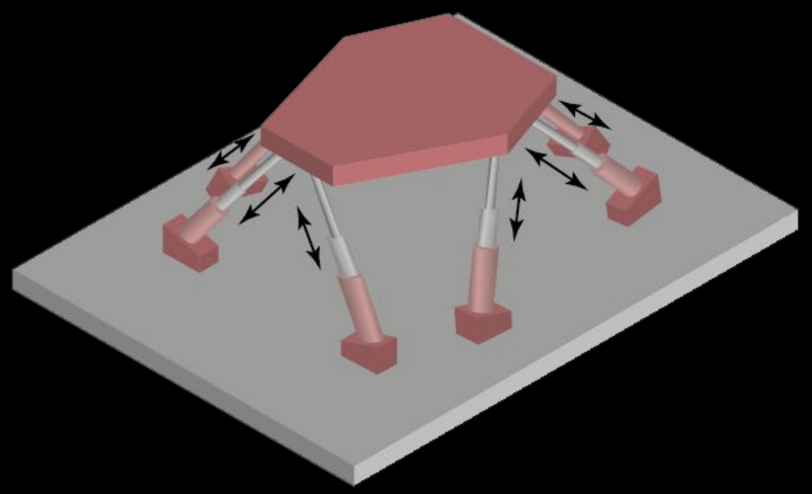


Mobility

- ✓ *Prismatic vs. revolute joints*

Degrees of freedom

- ✓ *3 for position + 3 for orientation*



Workspace

- ✓ *Portion of environment the manipulator's end-effector can access*

Wheeled Robots

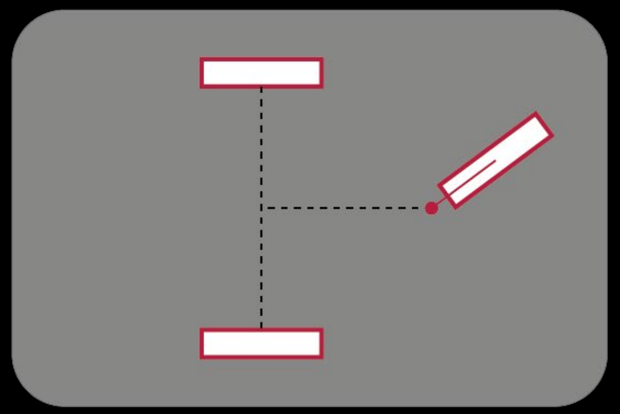
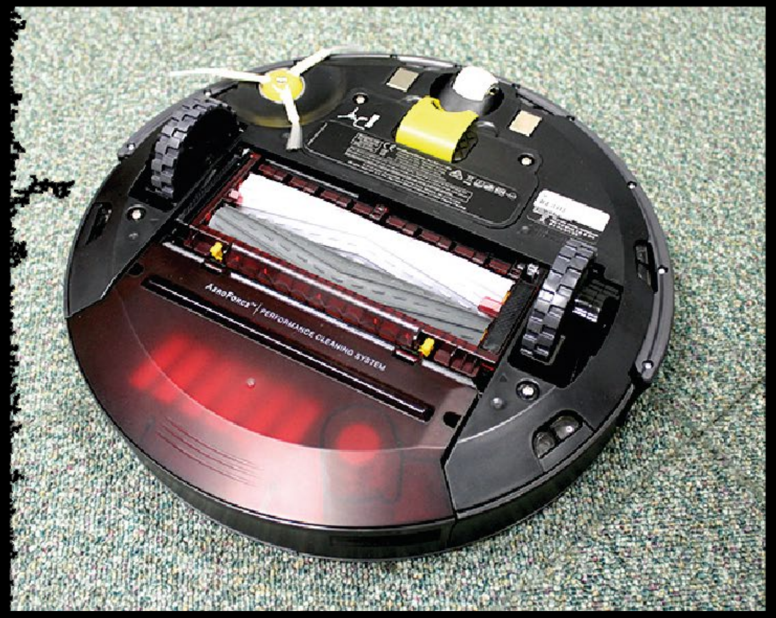
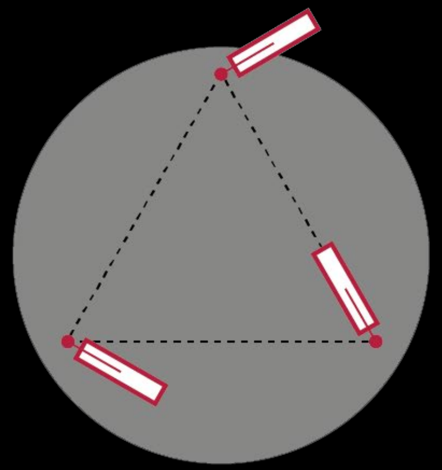
Mechanical structure of mobile robot: set of rigid bodies equipped with locomotion system

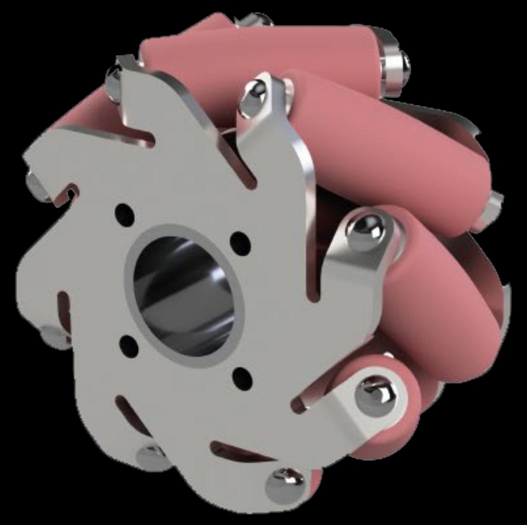
✓ *Mobile robots on wheels*

- *Base (chassis)*
- *Wheels that move it with respect to the ground*
- *Possible trailers (on wheels)*

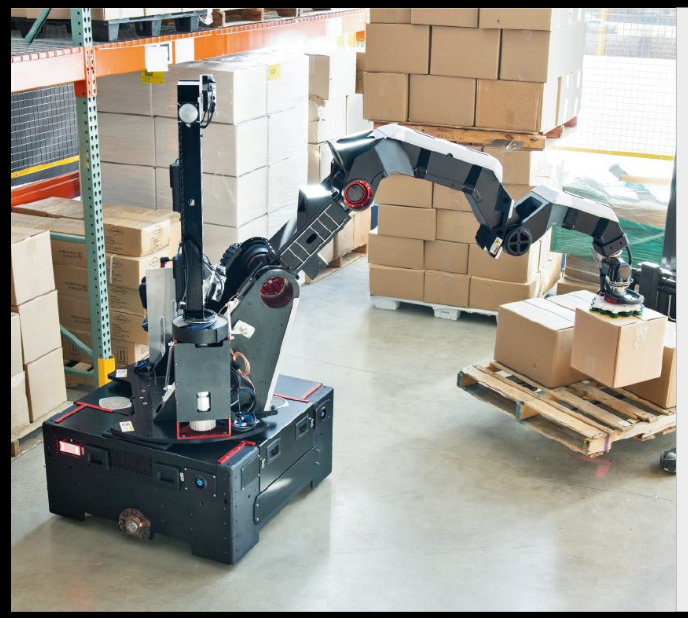
✓ *Mobile robots on legs*

- *Limbs*
- *Foot periodically in contact with the ground (locomotion)*
- *Project inspired by living organisms (biomimetic robotics)*

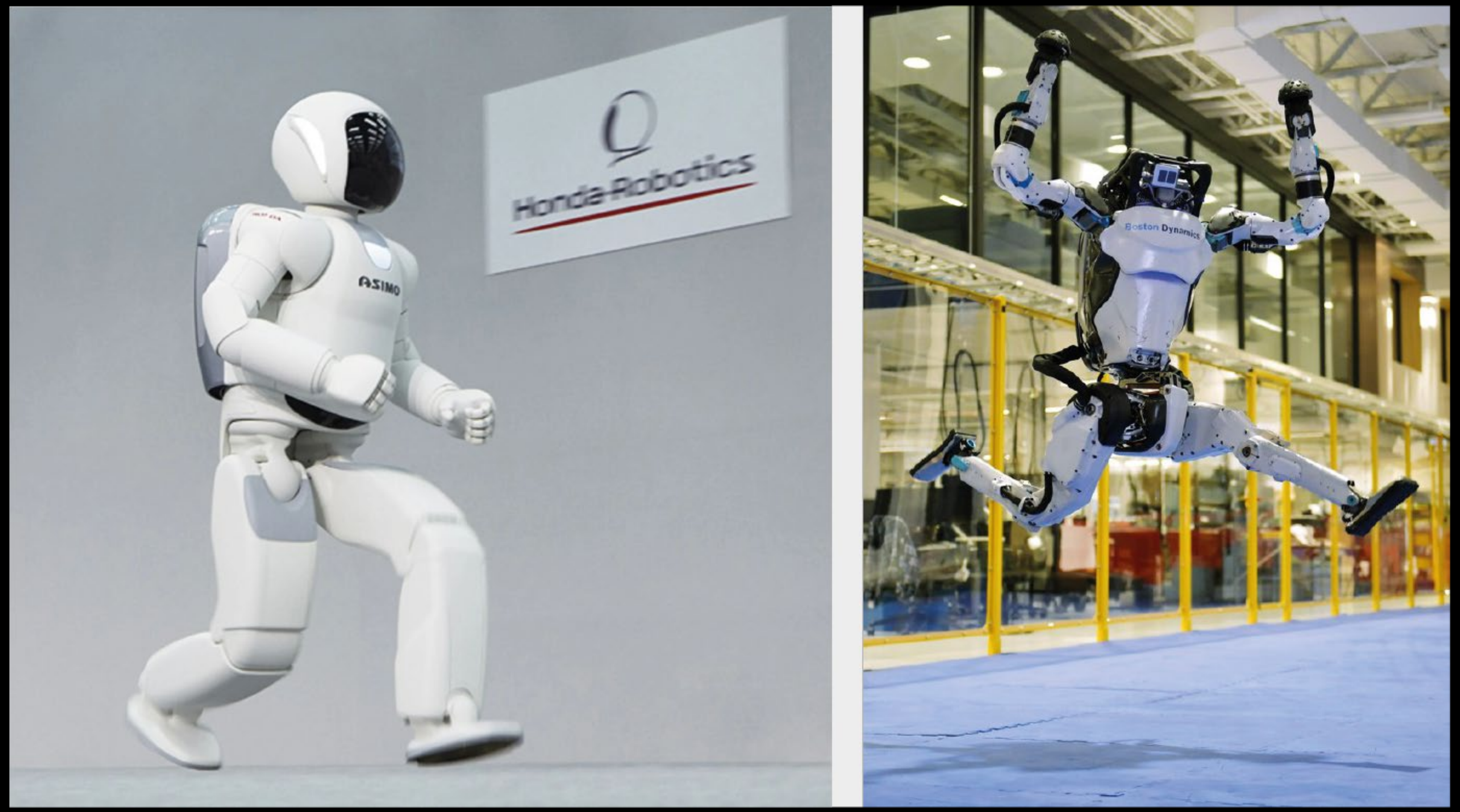










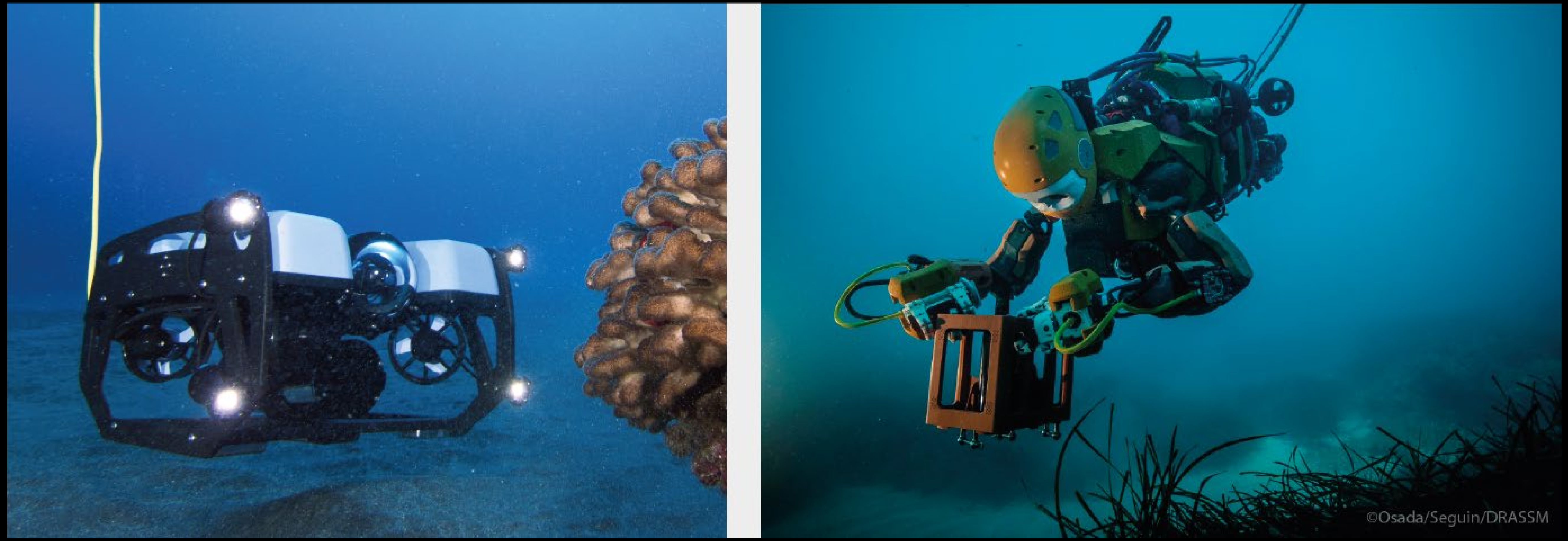

Other Robot Structures



Bipeds

Flying

Walking



Underwater

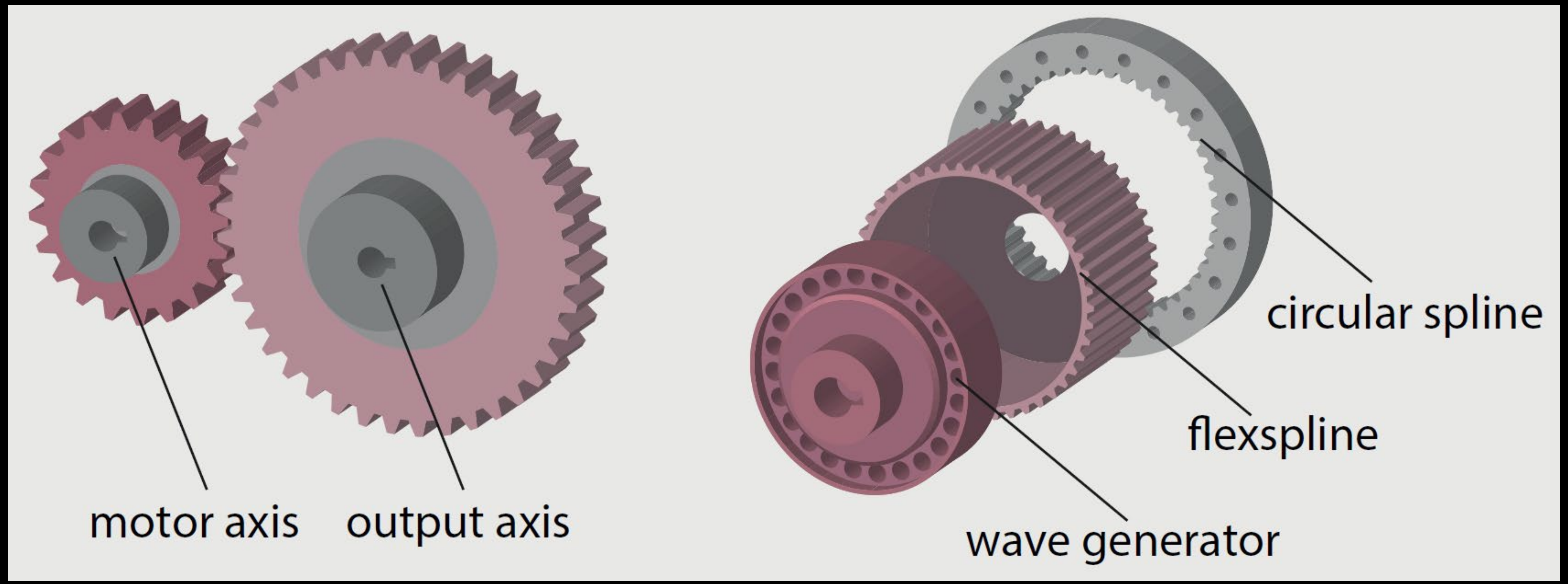
Actuation

Robot actuation is entrusted to motors which allow the realization of a desired motion for the mechanical system

- ✓ *Electric servomotors use as primary supply the energy available from the electric distribution system*
- ✓ *Hydraulic servomotors transform the hydraulic energy stored in a reservoir into mechanical energy by means of pumps and valves*
- ✓ *Pneumatic motors use the pneumatic energy provided by an air compressor and transform it into mechanical energy by means of pistons or turbines*

Transmissions

- ✓ *The execution of joint motions of a manipulator, as well as of wheel rotations in a mobile robot, demand low speeds with high torques*



Harmonic drive

Sensing

A key component for achieving high performance in robotic systems are sensors

Proprioceptive sensors

- ✓ *Joint position, velocity, and torque (in manipulators as well as other robots with revolute joints, e.g., legged robots)*
- ✓ *Angular position or velocity of wheels (in wheeled robots)*
- ✓ *Position, orientation, velocity and acceleration of a body of the robot (in mobile robots)*

Exteroceptive sensors

- ✓ *Forces and moments exerted by the robot on the environment*
- ✓ *Relative distance (range) and orientation (bearing) with respect to workspace obstacles, beacons, and such*
- ✓ *Visual data (images or cues) about the area surrounding the robot*

Control Architecture

The main component is intelligence, which is implemented as a control architecture

Deliberative architecture

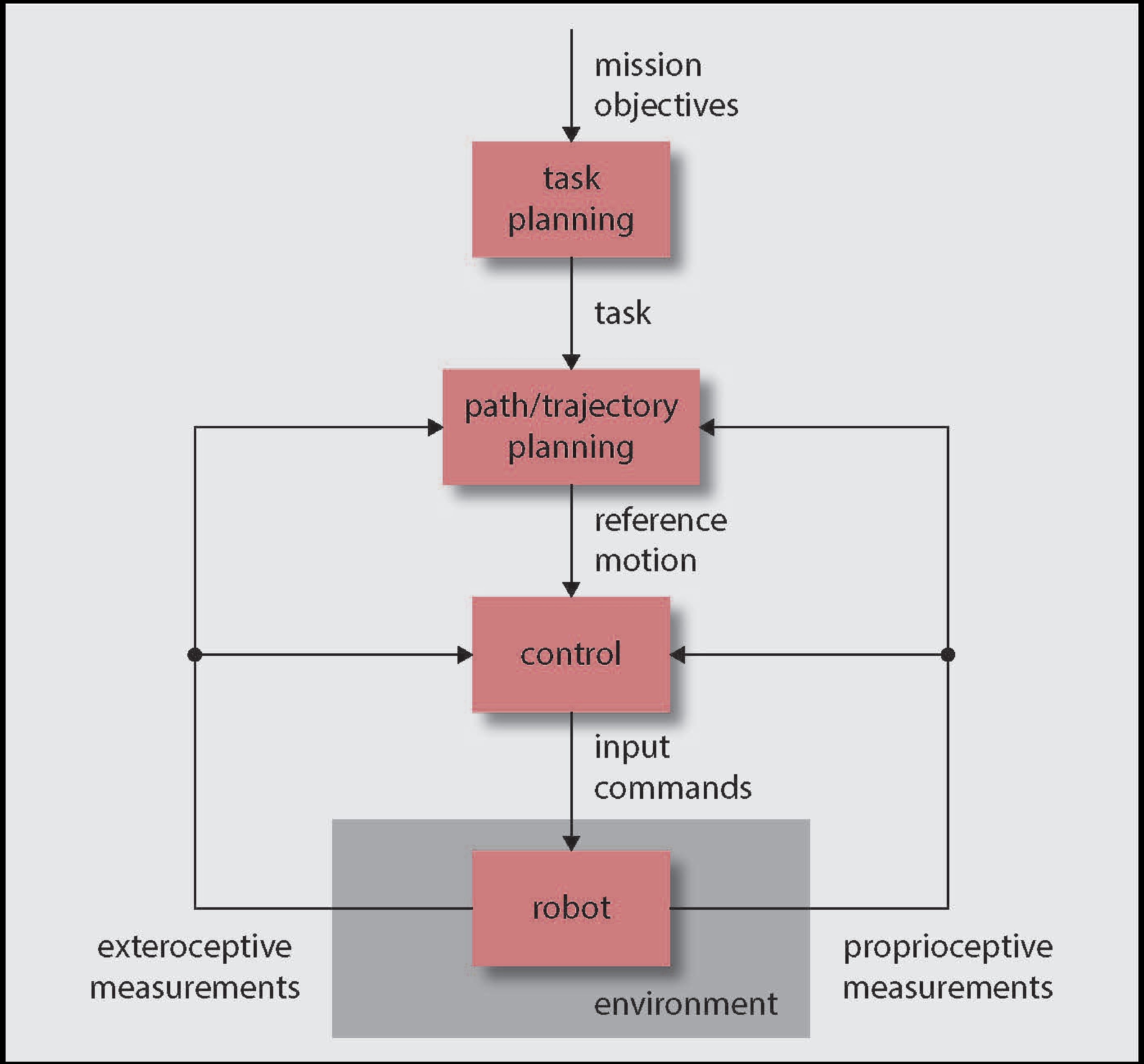
- ✓ *First Think, then Act*

Reactive architecture

- ✓ *Don't Think, React (bio-inspired)*

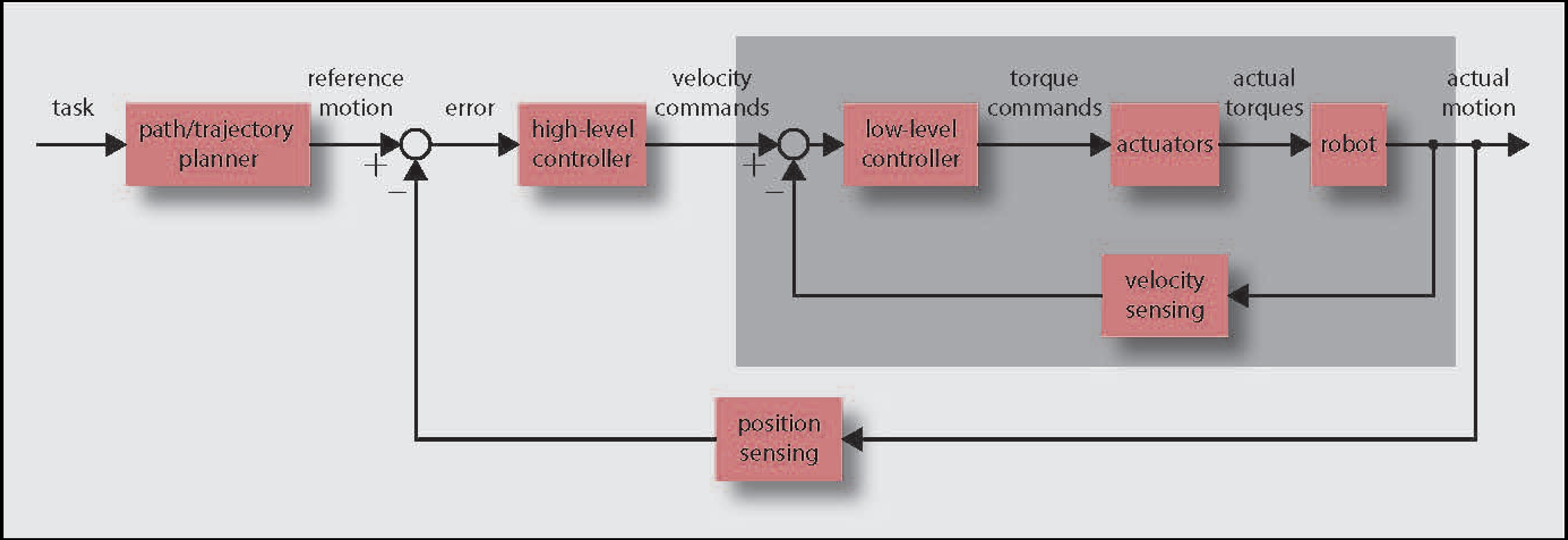
Hybrid architecture

- ✓ *Deliberation at higher level (motion planning)*
- ✓ *Low-level functionalities via reactive modules*



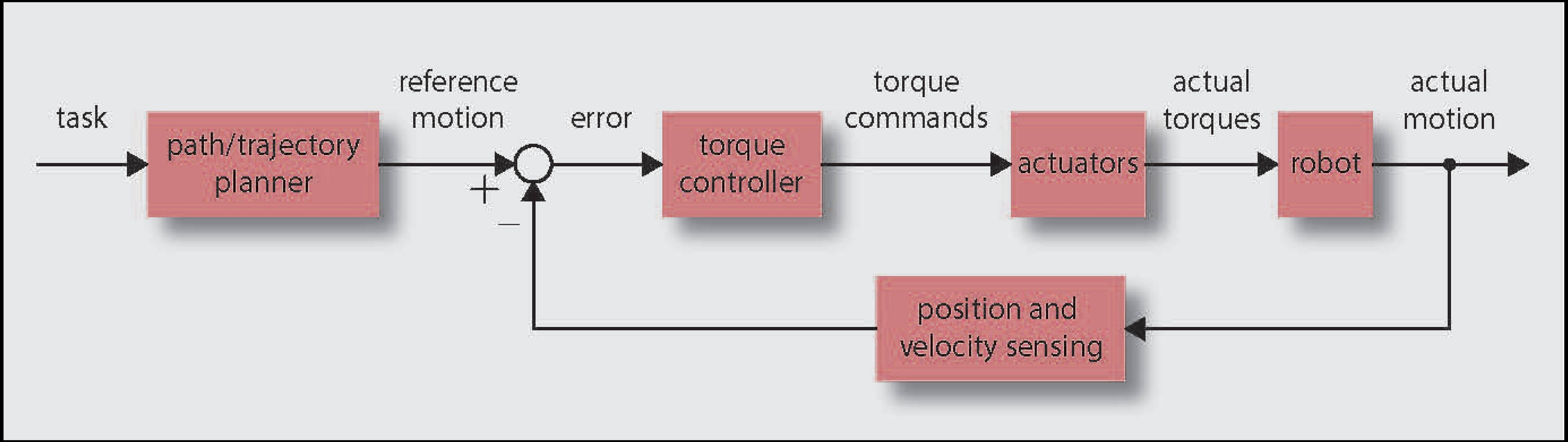
Velocity-Controlled Robots

Looking at the robot as an essentially kinematic mechanism (kinematic control)



Torque-Controlled Robots

Accounting for the full dynamics of the robot (dynamic control)



- ✓ *Typical control frequencies for both velocity-controlled and torque-controlled robots range from 100 Hz to 1 KHz*

Artificial Intelligence

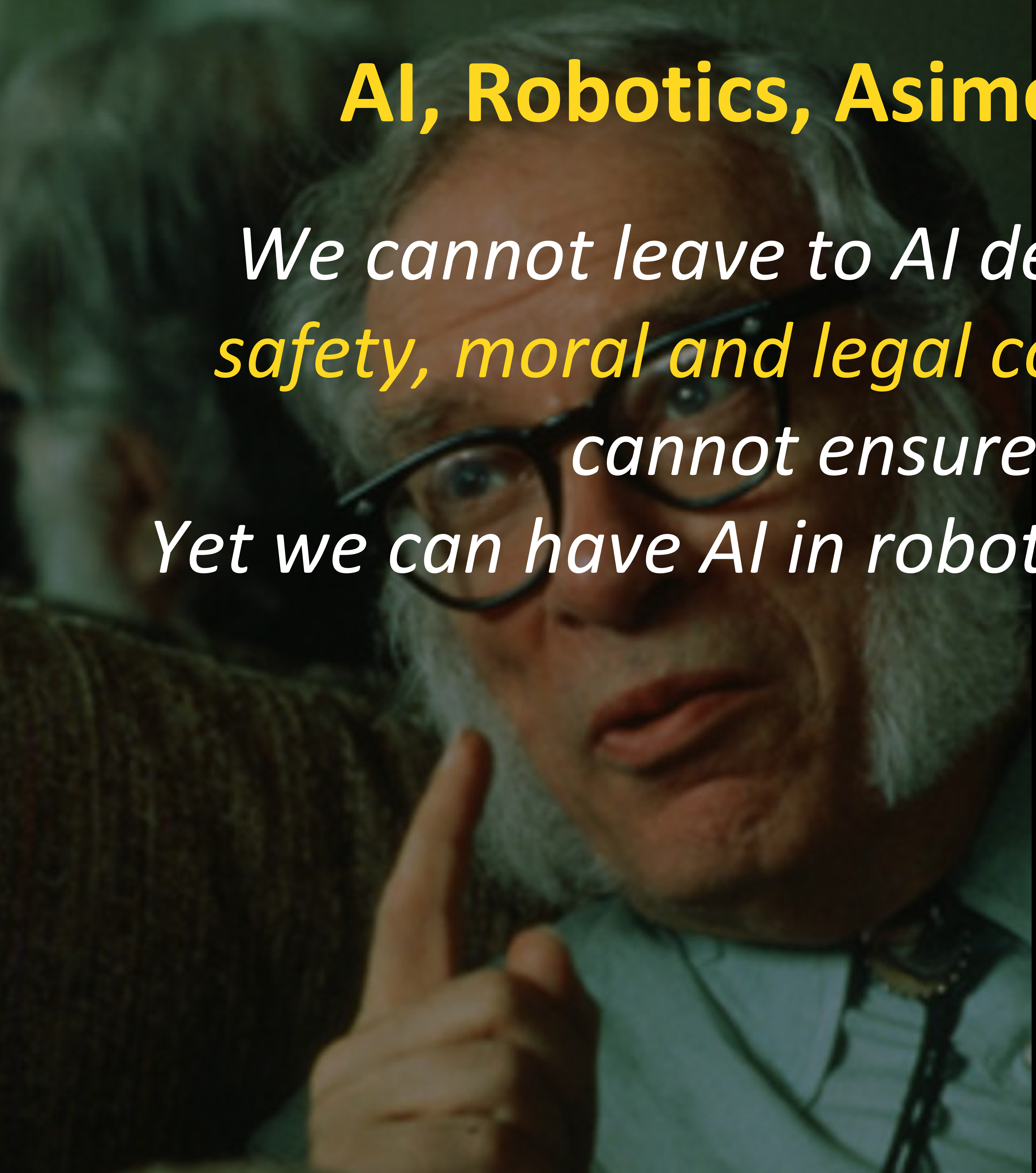
Computers mimicking functions and logics of human mind

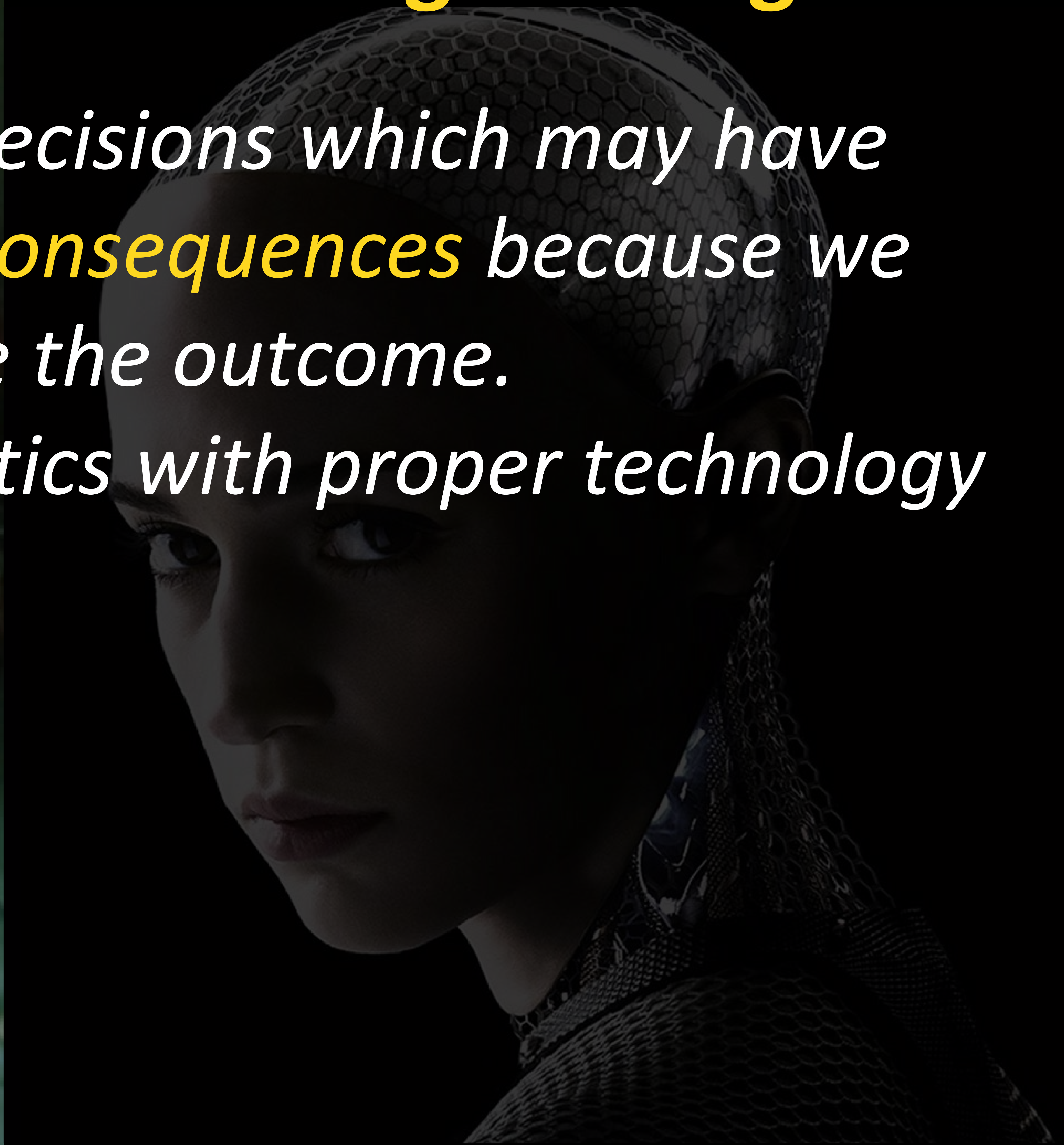
Cortical homunculus

AI, Robotics, Asimov and Engineering

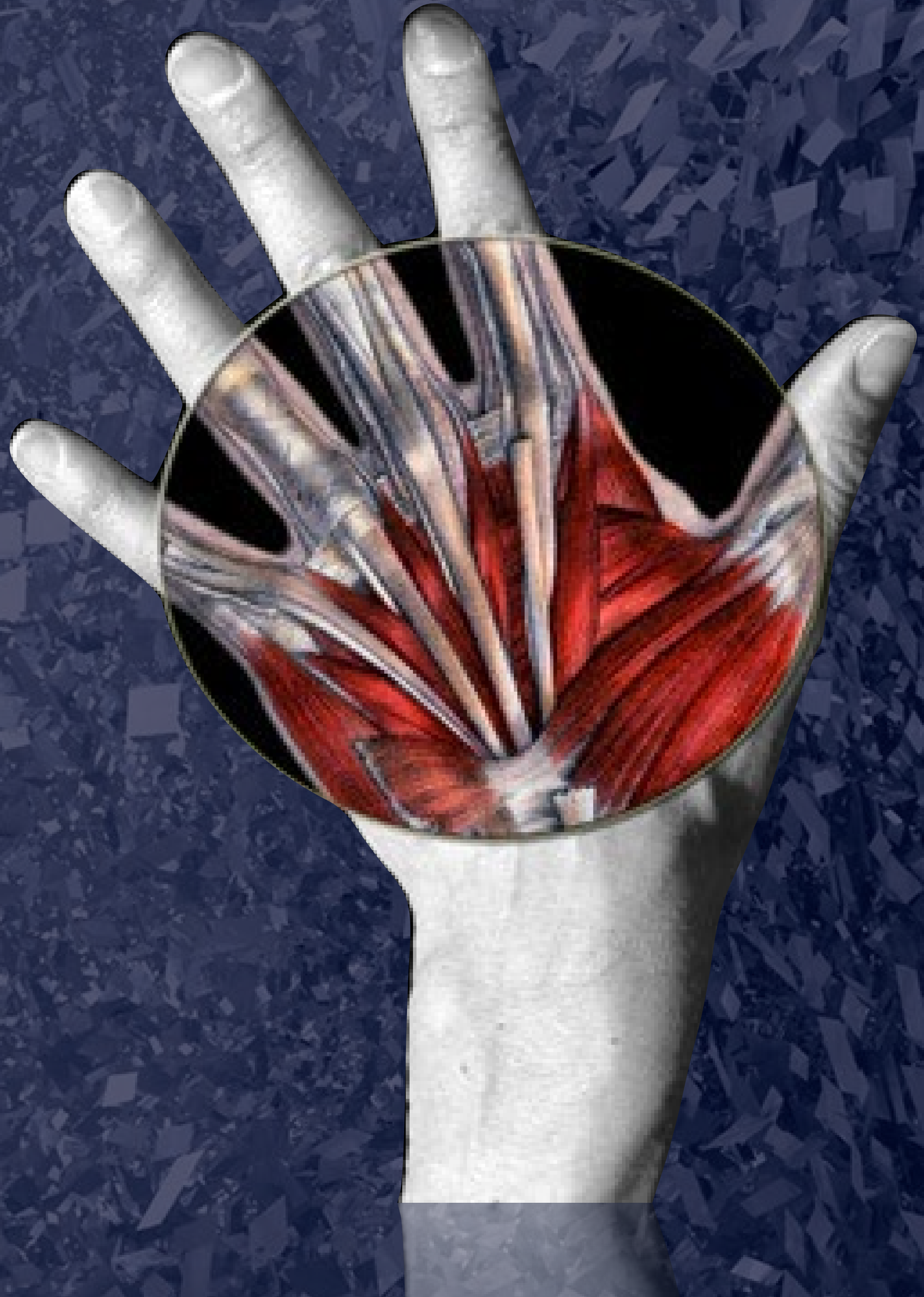
We cannot leave to AI decisions which may have safety, moral and legal consequences because we cannot ensure the outcome.

Yet we can have AI in robotics with proper technology





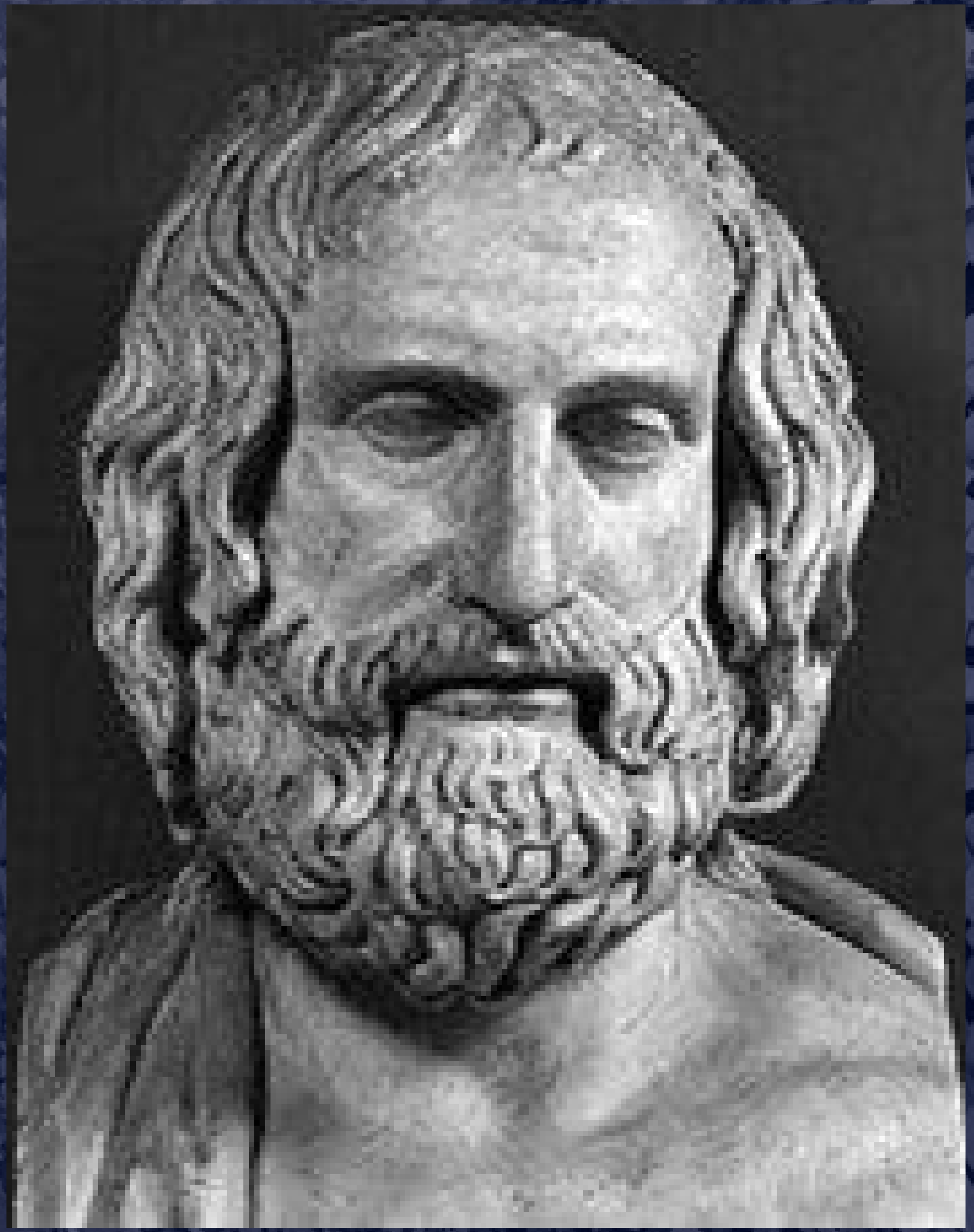
The Big Challenge



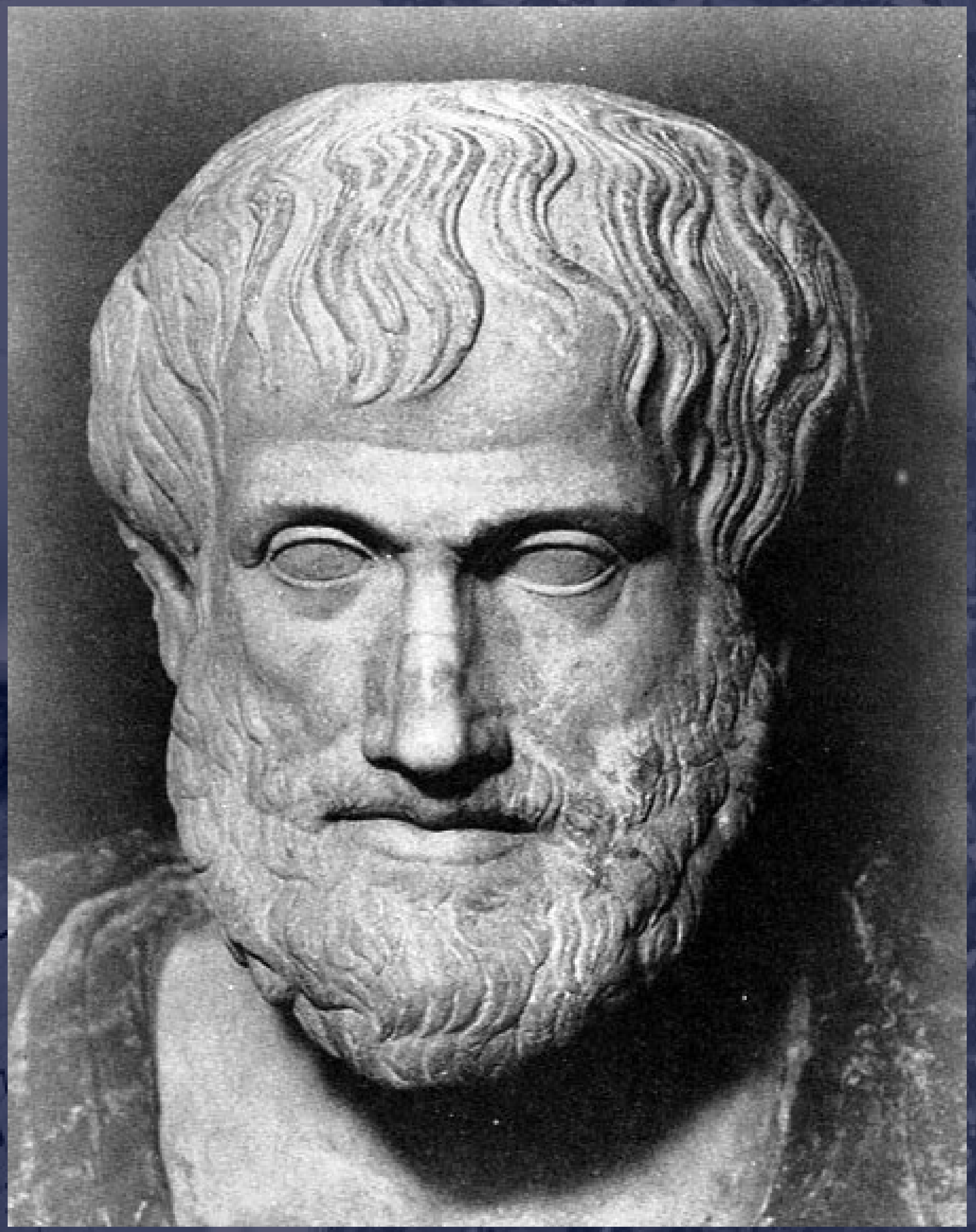
Manipulation

Cognition

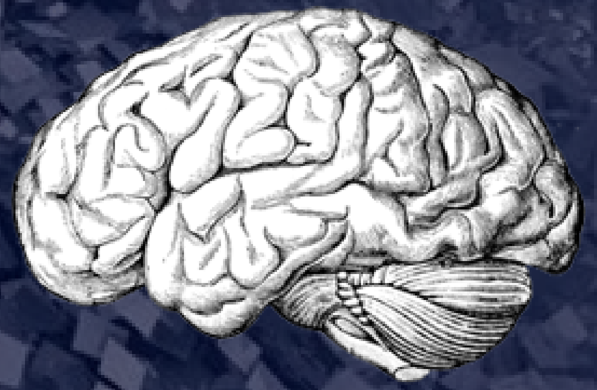
Body vs Mind



Anaxagoras

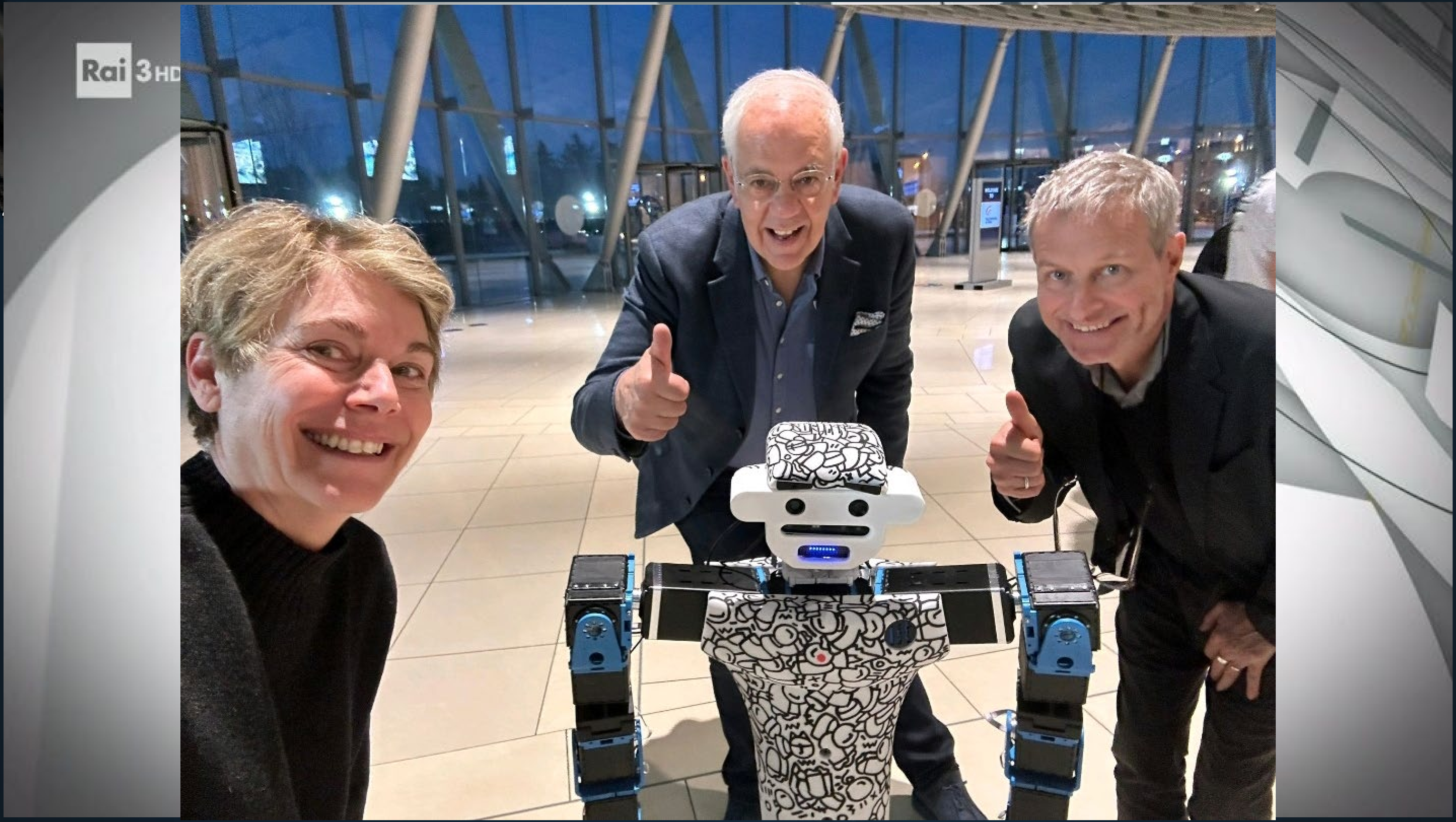


Aristotle



Embodiment

Fleshing out AI



Physical Human–Robot Interaction

… from Information & Communication Technology (ICT)
to InterAction Technology (IAT)

Nature Italy, Antonio Bicchi & Bruno Siciliano (2021)

Industry 4.0

n–Robot
eration
obot)

CRAFT ERA → MASS PRODUCTION ERA → MASS CUSTOMIZATION ERA

Cobot

Collaborative robot (Cobot)

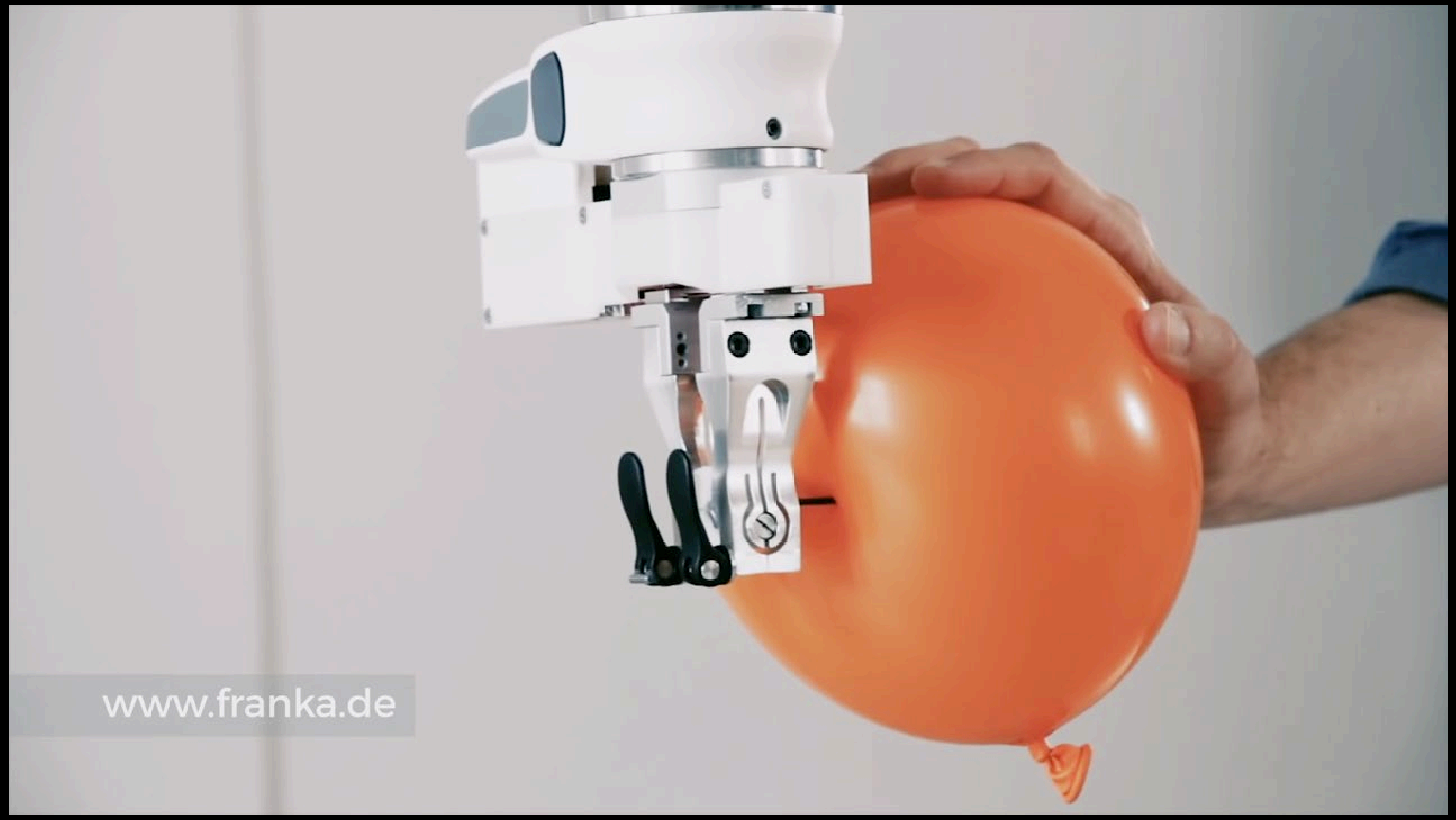
✓ *Can be used safely in a space shared with humans*

✓ *Special mechanical characteristics, extroceptive sensors, advanced control system*

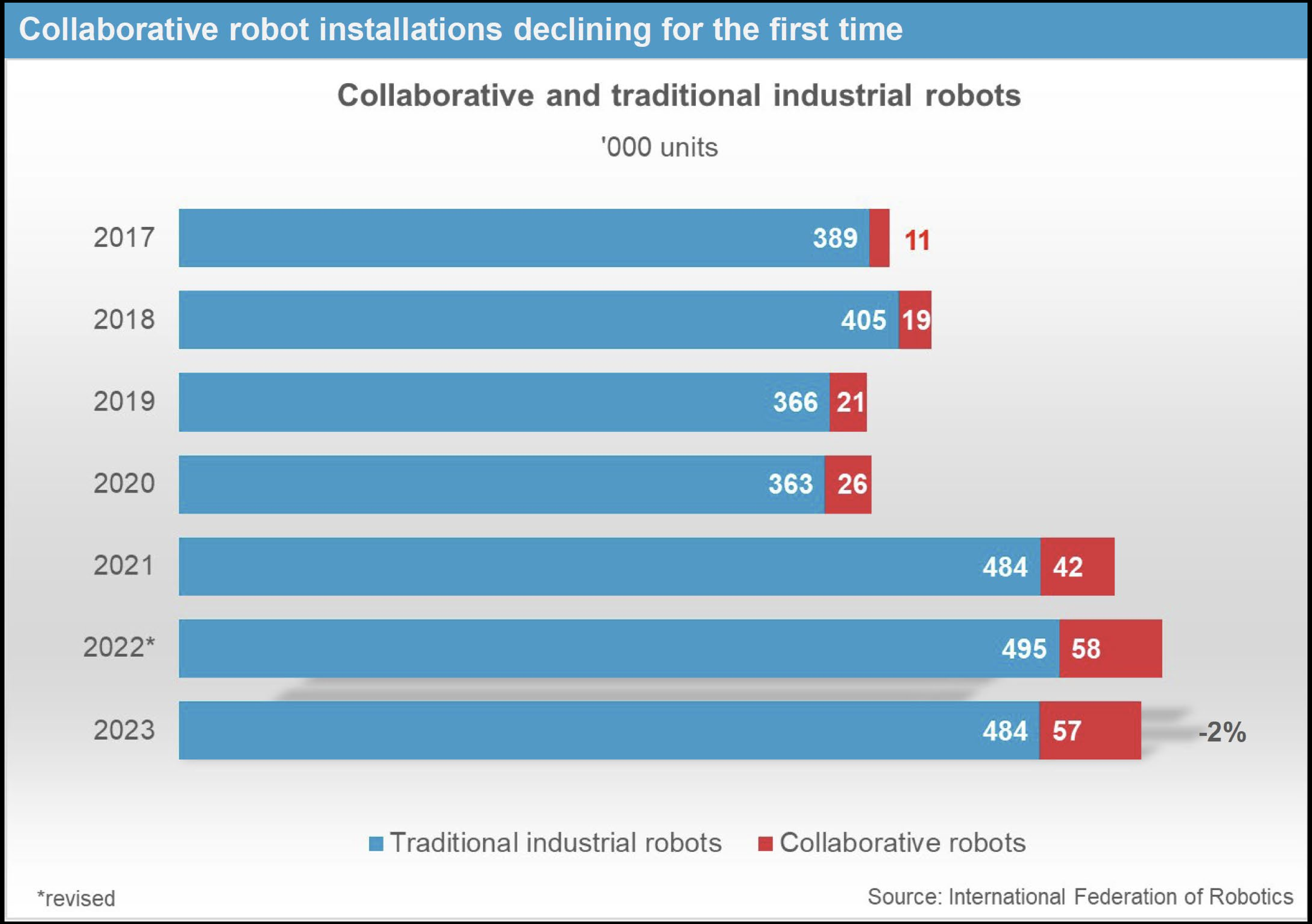
✓ *Intuitive programming and communication interface*

✓ *Fast setup, commissioning, and reconfiguration*

✓ *Low costs (<20k) and suitable for Small and Medium Enterprises (SMEs)*

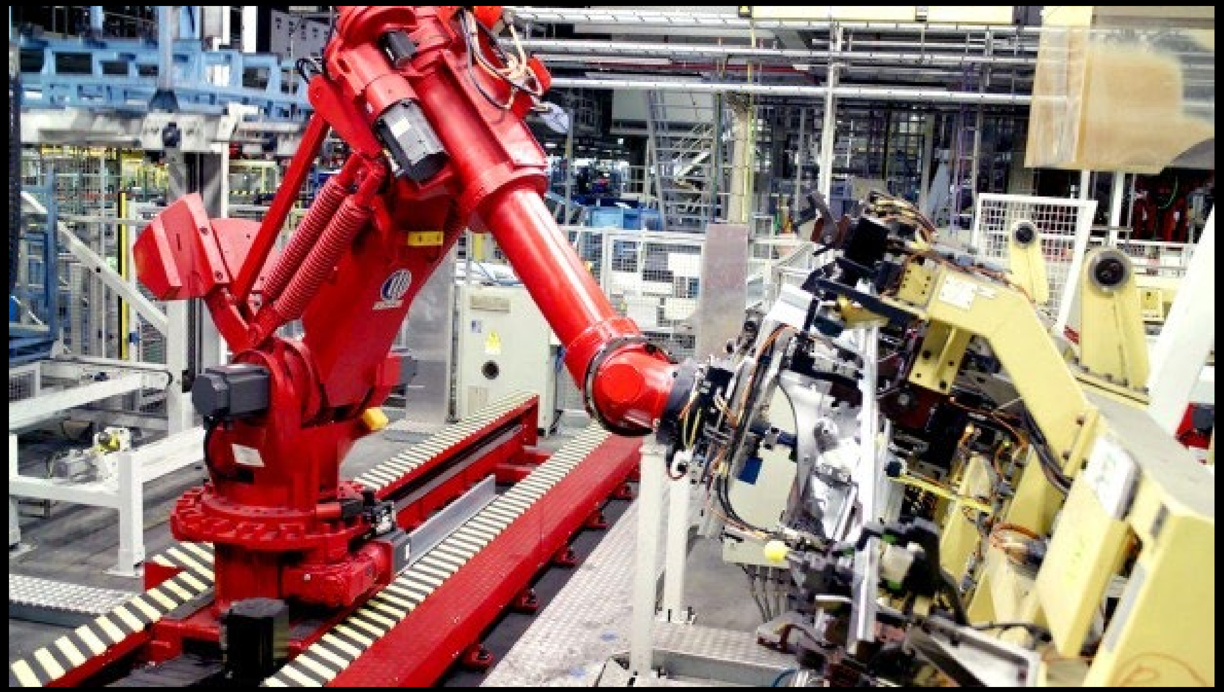


Collaborative vs Traditional Industrial Robots

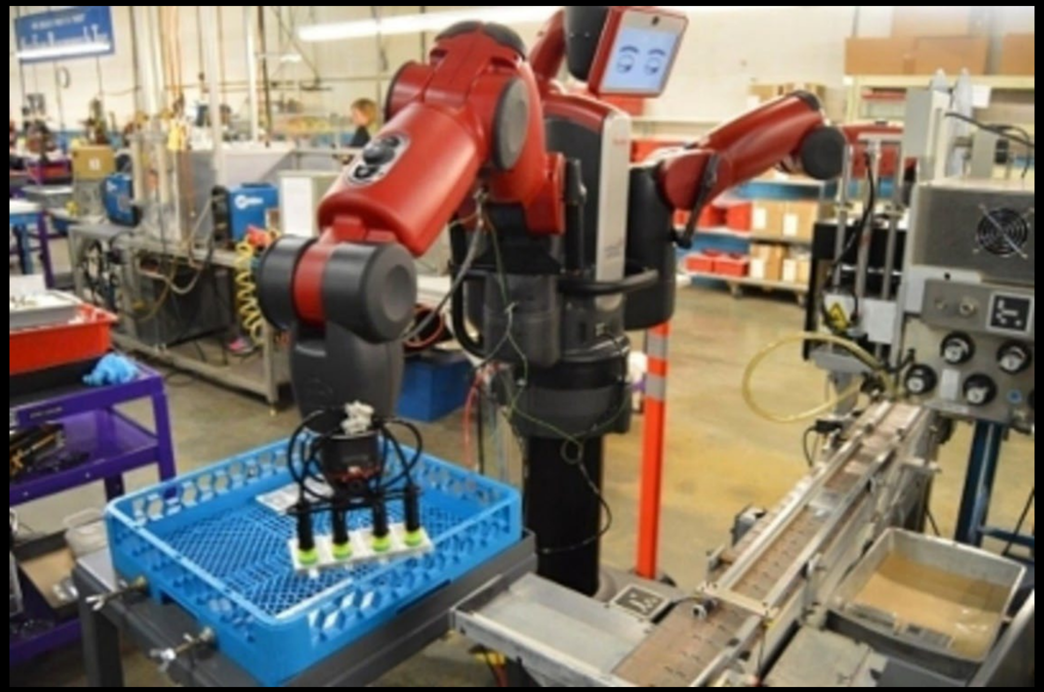


From Factories to Our Homes

LEVEL OF AUTONOMY

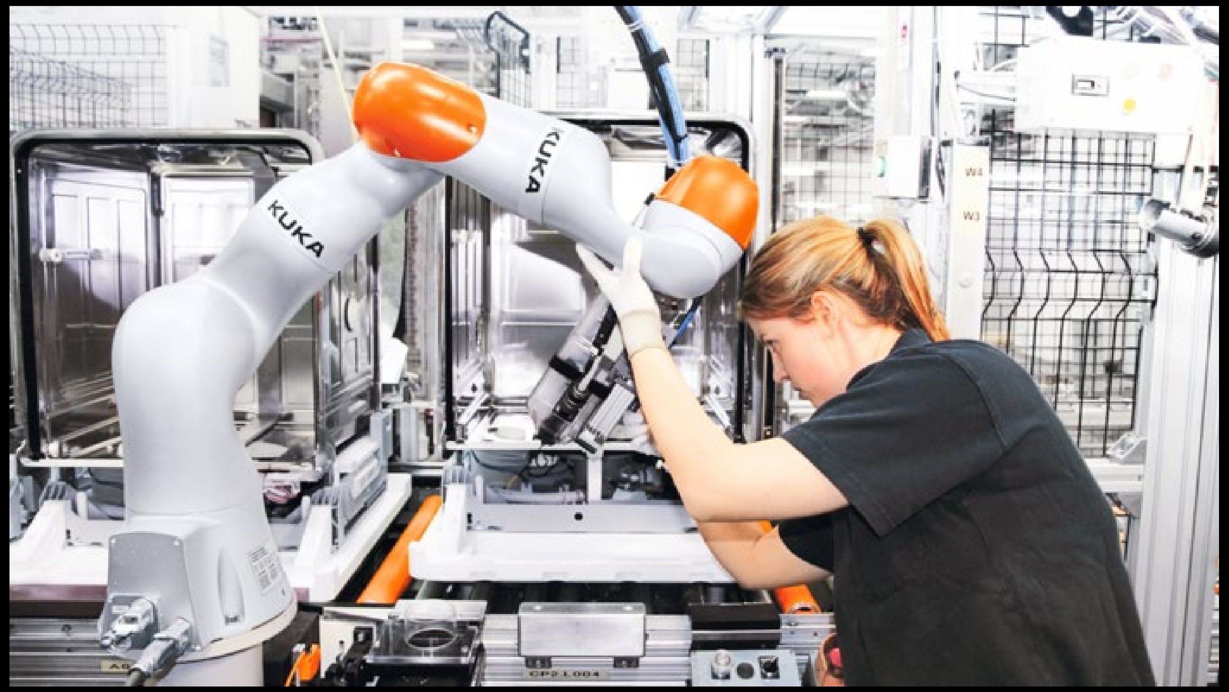


Automatic machines executing programmed tasks with high levels of accuracy, speed and repeatability in a perfectly known environment



Machines equipped with sensors (vision, distance, force, …) for perceiving the external environment and with decision-making capabilities

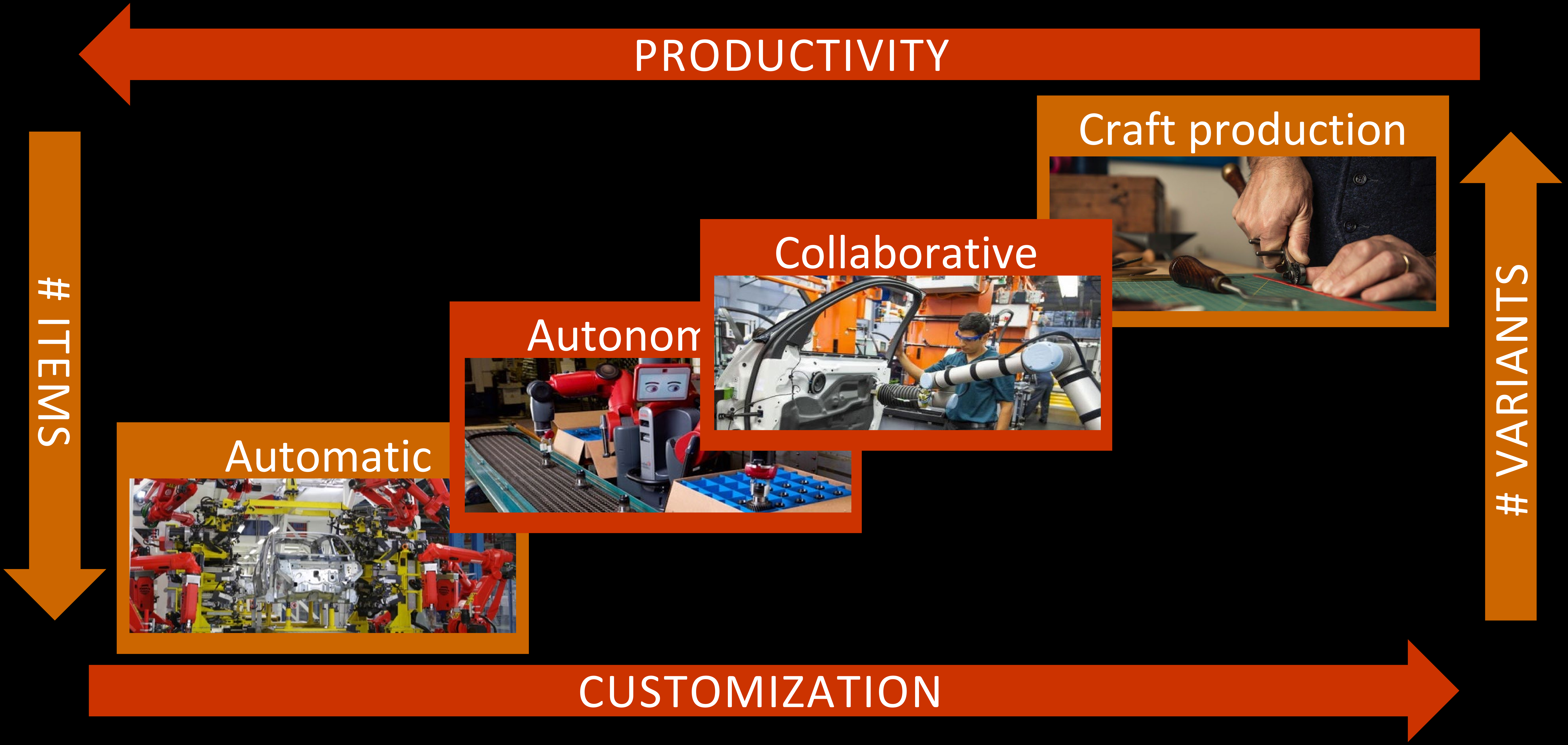
Machines confined in fenced areas, designed to handle the dull, dirty and dangerous tasks in place of human workers



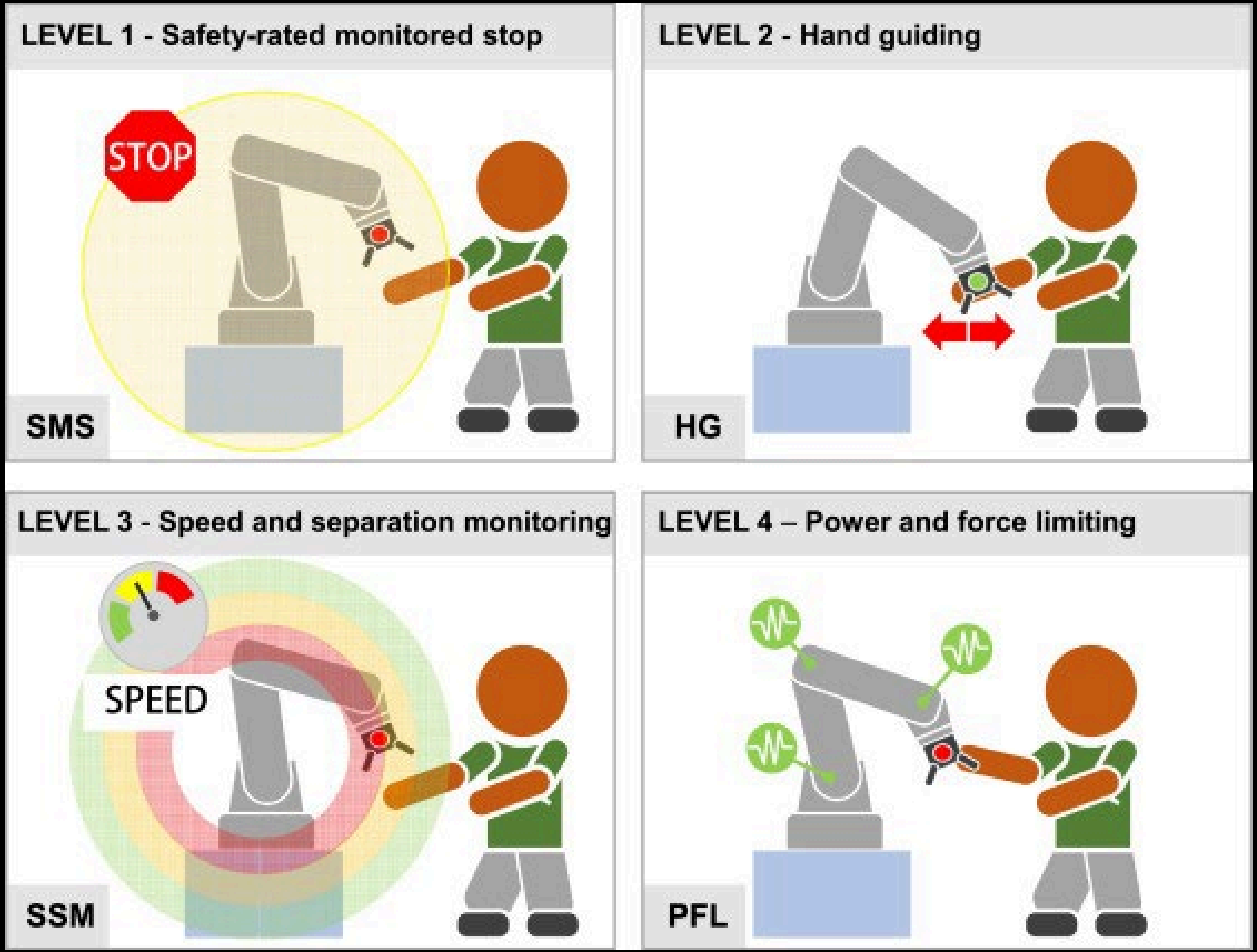
Lightweight machines able to work safely in the same workspace or even physically collaborate with humans

SAFETY AND COLLABORATION CAPABILITY

From Mass Production Towards Mass Customization



Safety



4 levels of collaborative operations

Safety standards

- ✓ *ISO 10298-1/2 --> safety requirements and guidelines for robots in industrial environments*
- ✓ *ISO/TS 15066 --> technical specifications for collaborative robot system safety*

Cobots Hardware & Software

Mechanics

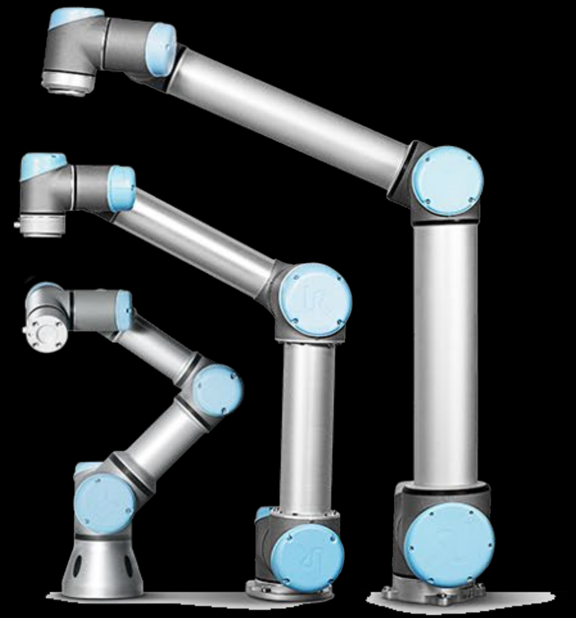
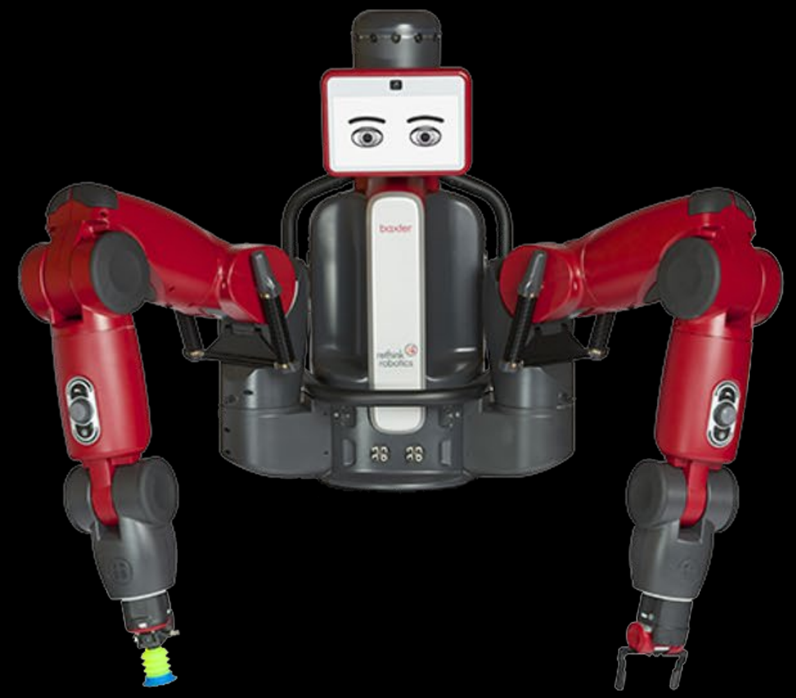
- ✓ *Lightweight*
- ✓ *Redundant/double arms*
- ✓ *Soft covers, no edges*
- ✓ *Elastic joints*

Sensors

- ✓ *Joint torques*
- ✓ *Force/torque at the end-effector*
- ✓ *3D vision*
- ✓ *Sensitive skin*

Control

- ✓ *Compliant, collision detection, collision avoidance*
- ✓ *Coexistence / cooperation / collaboration*


Programming Interfaces

Traditional programming modalities

- ✓ *On-line lead-through (teach pendant)*
- ✓ *Off-line*

Intuitive programming interfaces

- ✓ *On-line walk-through (manual guidance)*
- ✓ *Training by demonstration*
- ✓ *Virtual and augmented reality*
- ✓ *Multimodal communication (gestures, voice, touch)*

Robots & Humans Working as One

Wearable robots: Exoskeletons

- ✓ *Composed by a frame fitted with (motorised) muscles supporting parts of the human body*
- ✓ *Allow multiplying the strength of its user's or redistributing the weight*
- ✓ *Enable workers to carry out a variety of industrial tasks*
- ✓ *Protect workers from the heavy physical workload, repetitive movements and non-ergonomic postures*


arm support


back support

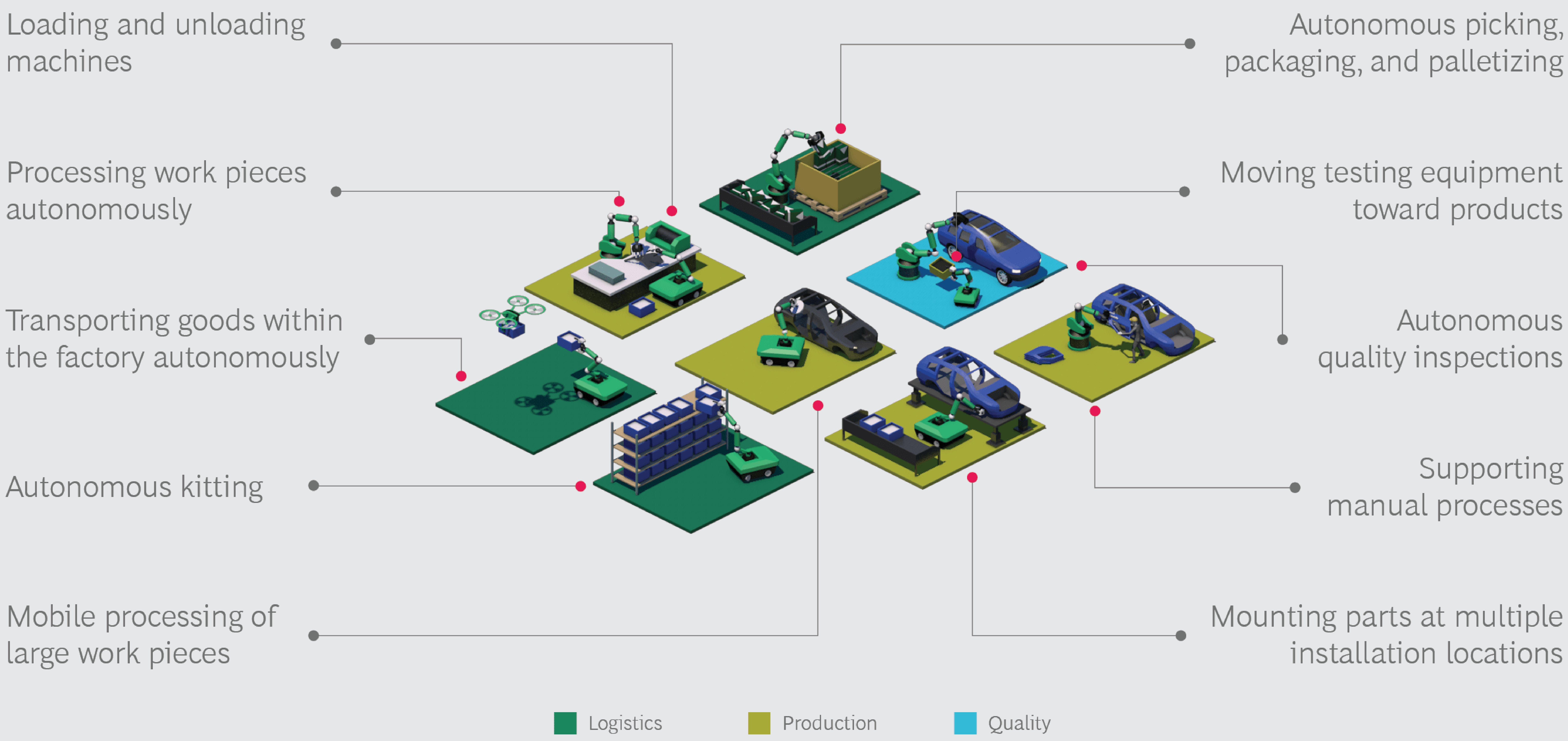

legs support


tool holding

https://exoskeletonreport.com

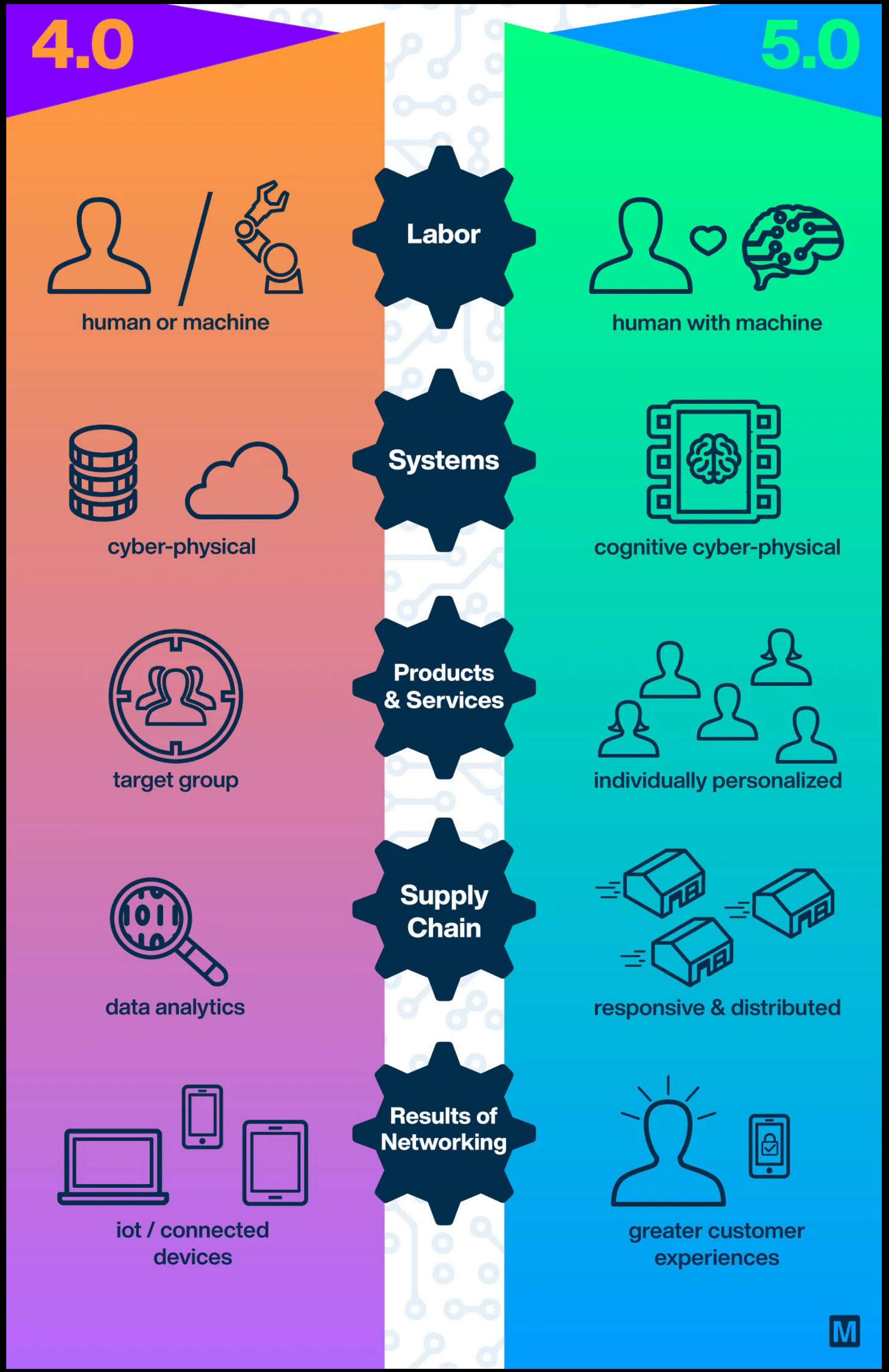
The Factory of the Future

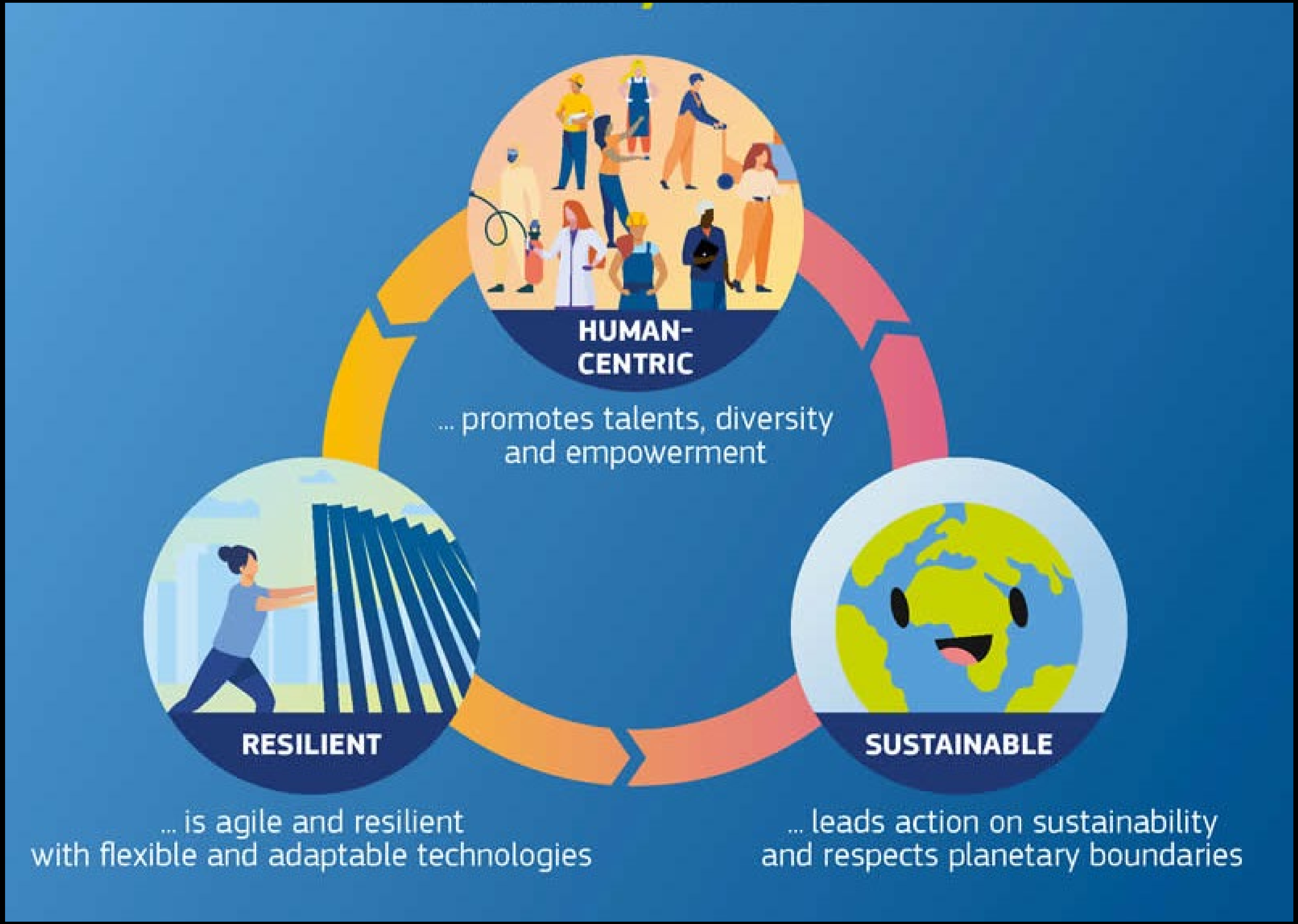
EXHIBIT 3 | Advanced Robotics Has Many Applications in the Factory of the Future



Sources: BCG Global Advanced Robotics Survey, January–February 2019; BCG analysis.

Towards Industry 5.0



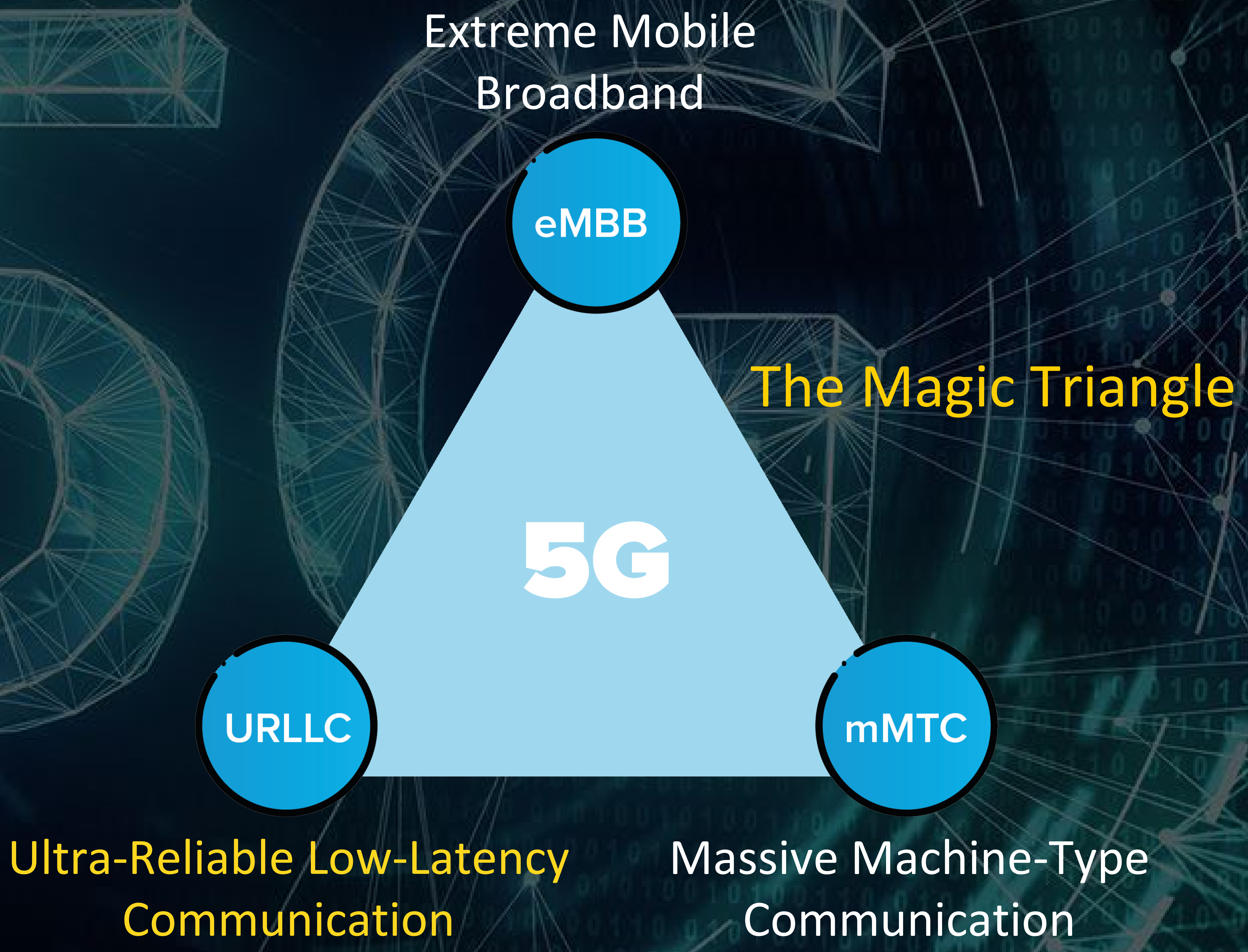


Fifth Generation of Wireless Technology

5G will pave the way for a new generation of robots

The vast computing and data storage resources of the cloud is exploited

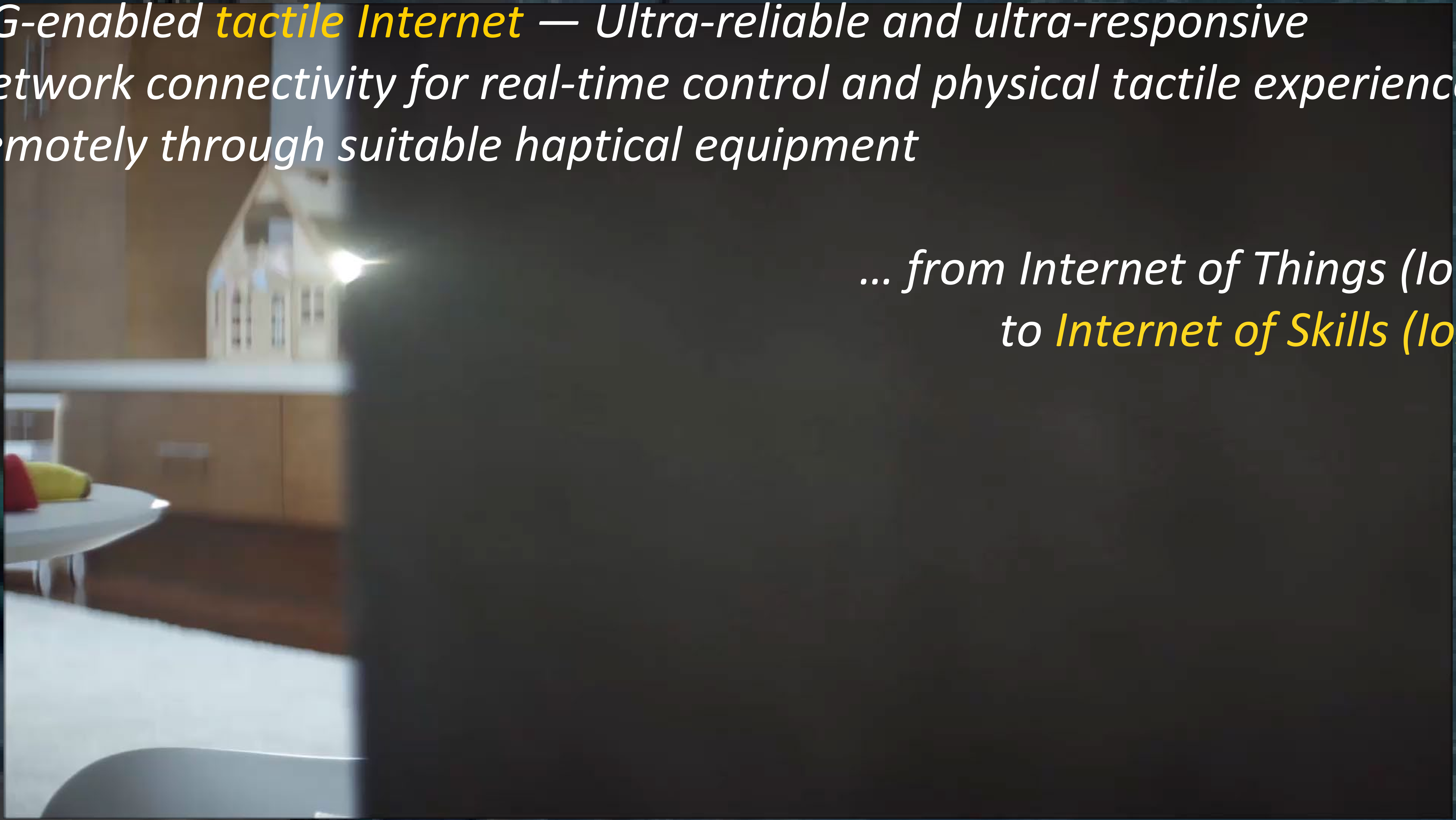
Robots can be controlled dynamically in real time and be connected to people and machines locally and globally



The Invention Age

5G-enabled tactile Internet — Ultra-reliable and ultra-responsive network connectivity for real-time control and physical tactile experience remotely through suitable haptical equipment

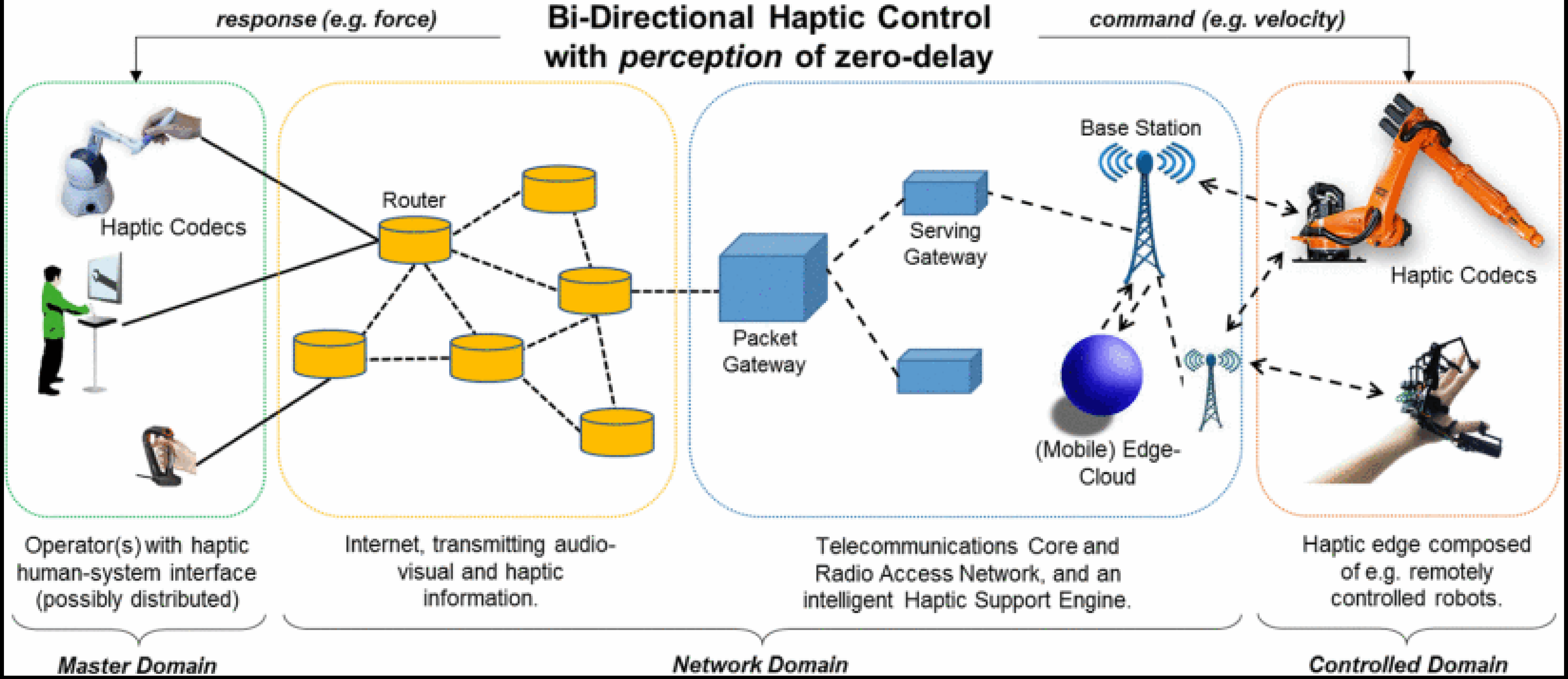
… from Internet of Things (IoT)
to Internet of Skills (IoS)



Towards a Digital & Physical Twin — The Phygital

1) **Ultra-Fast Networks** (Tactile Internet)
2) **Haptic Encoders** (both kinestaethic & tactile)
3) **Edge Artificial Intelligence** (to beat light-limit)

Core Technology Enablers of the "Internet of Skills"



Pillars of Next Generation Robotics

The Factory, Reimagined

NDT, Autonomous

The AI Data Robotics Association

euROBIN

Healthcare, Revolutionized

Robots on the Field, Unthetered

Robots as Job Killers?

Identify which forms of protection are morally right to put in place to protect workers who will face technological unemployment in the short term, but also to deal with possible and unprecedented effects in the long term, if the impact of intelligent machines actually constitutes a singularity in the history of automation

https://willrobotstakemyjob.com/

Robots as Green Tools?

Restoration and protection of our ecosystem towards the development of a new generation of technologies capable of coexisting harmoniously with the environment

Reduction of Carbon Footprint

Modern robots are energy-efficient, thus directly reducing energy consumption of production

Through higher precision, they also produce fewer rejections and substandard goods, which has a positive impact on input/output resources

Robots help in the cost-efficient production of renewable energy equipment, such as photovoltaics or hydrogen fuel cells

IFR International Federation of Robotics

https://ifr.org

Decarbonizing the Built World

Gecko Robotics, a company at the forefront of using Robotics and AI-powered software to improve the health of the physical world, partenered with Rho Impact, a leading impact analytics firm, to understand the environmental impact of digitizing critical infrastructures

The research findings emphasize the importance of leveraging robotics, sensors, and digitization to unlock new industrial efficiencies, reduce waste, and minimize the carbon footprint of the manufacturing sector

gecko

RHOIMPACT

January 2024

The Impact of Robotics and AI

Better use of Robotics and AI could result in an impressive reduction of 853 million metric tons (MMT) annually, equivalent to 18% of U.S. CO_2 emissions (CO_2e), or eliminating more than half (64%) of the gas-powered vehicles on the road

Through robotics-enabled digitization, the following reductions could be achieved by 2030:

- ✓ *Oil & Gas Pipelines: 556 MMT CO_2e*
- ✓ *Baseload Power Plant Reliability: 230 MMT CO_2e*
- ✓ *Pulp & Paper Manufacturing: 46 MMT CO_2e*
- ✓ *Maritime Transportation: 11 MMT CO_2e*
- ✓ *Bridge Inspection & Maintenance: 10 MMT CO_2e*

Reduce Fugitive Emissions from Oil & Gas Pipelines

Fugitive emissions are the unintended release or leakage of gases, including greenhouse gases, from equipment including piping, tanks, valves, and more

Early detection of corrosion can lead to a 556 MMT CO2e per year reduction in fugitive emissions from failed pipelines

Diminish Forced Outages

A primary culprit for forced outages is boiler tube failures, which increase as industrial assets age

Digitization of boiler tubes at energy generation sites could lead to a potential 230 MMT CO_2e reduction per year, all by keeping more efficient baseload generation online and inefficient backup generation offline

Optimize Asset Efficiency in Manufacturing

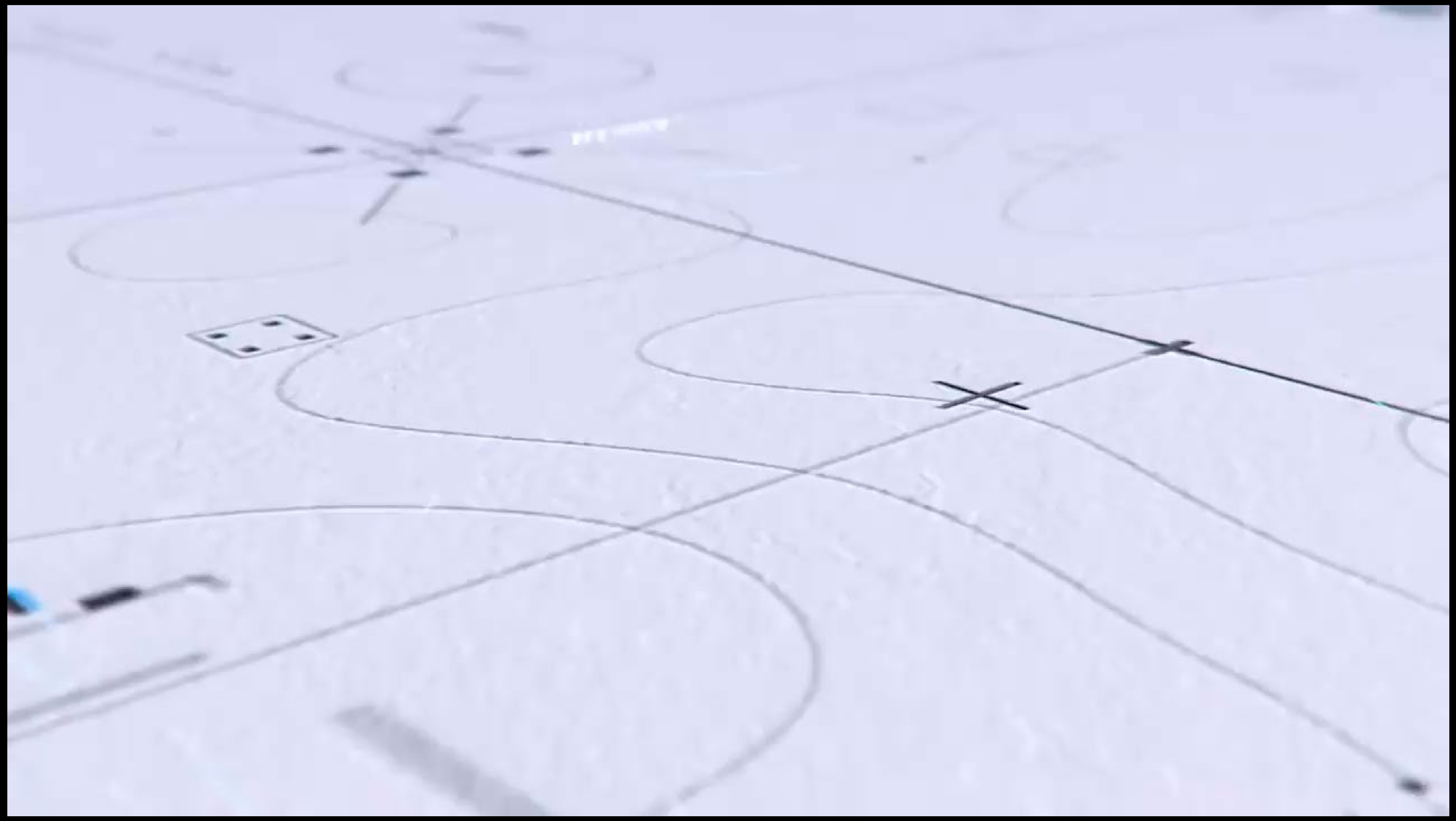
Corrosion is a major problem in the manufacturing industry, causing billions of dollars in damage each year

Digitizing key physical assets in the pulp & paper industry could result in an annual reduction of 46 MMT CO2e

Increase Maritime Vessel Availability

Load optimization and leak detection present significant opportunities for addressing greenhouse gas emissions in maritime shipping

Digitization could avoid 11 MMT CO2e per year by improving availability of the largest, most efficient shipping vessels



Decrease Traffic Emissions Through Bridge Digitization

Transportation agencies advise deploying robots for inspection and maintenance

Inspection digitization ensures better data on bridges, fewer closures, and effective maintenance, potentially reducing traffic-related emissions by 10 MMT CO2e yearly

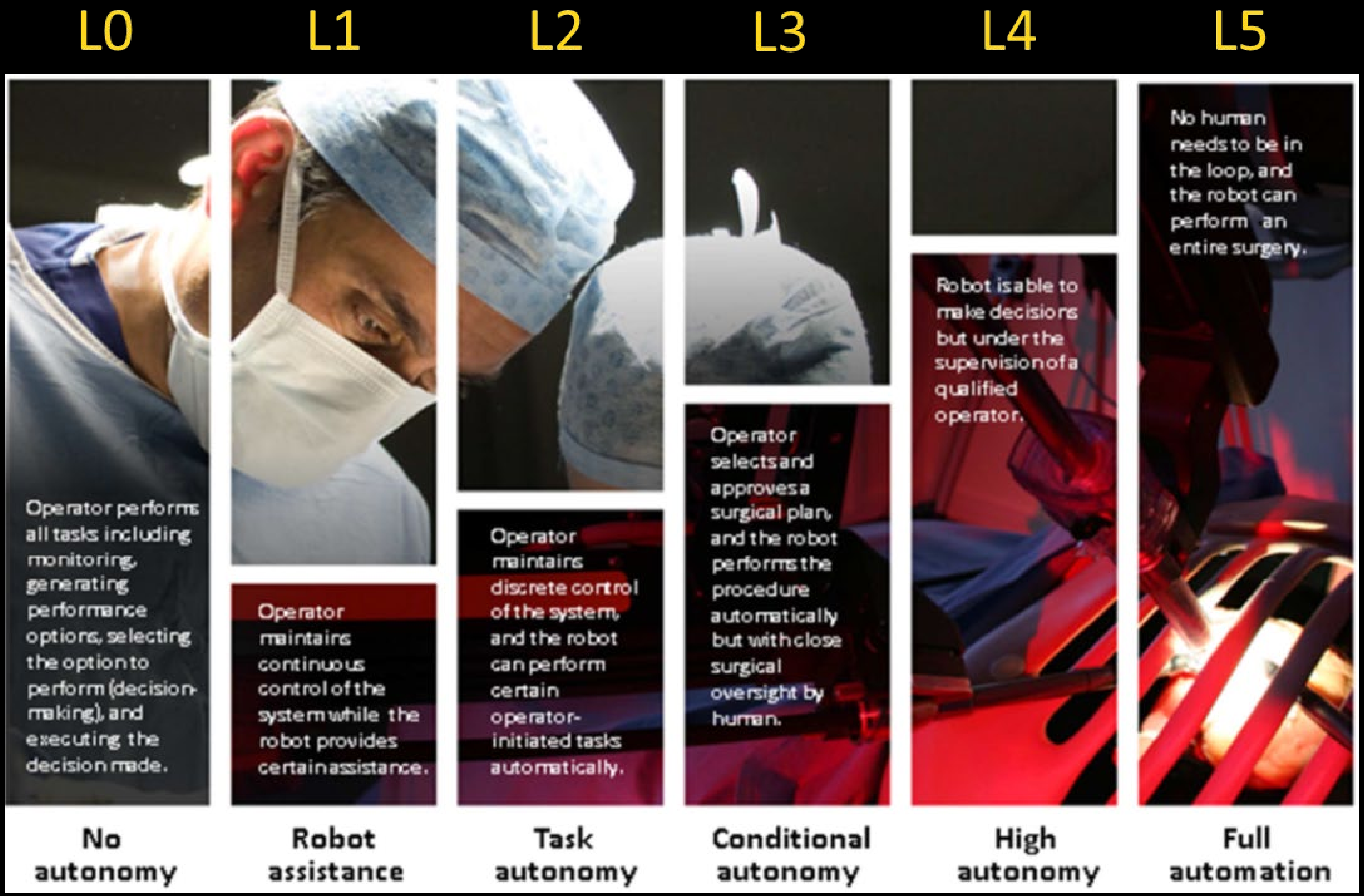
Towards Climate Neutral, Circular & Digitized Industry

- ✓ *Technologies for continuous learning and the integration of perception and actuation with natural and artificial intelligence*
- ✓ *Technologies to improve intuitiveness, usability and ergonomics of human–robot interfaces, allowing the effective use of robots by people without specific training*
- ✓ *Technologies using new materials, smart sensors and actuators, control architectures to ensure stability and safety*
- ✓ *Technologies for dexterous manipulation and locomotion in airborne, aquatic, underground environments and on terrains of varied and uneven nature*
- ✓ *Technologies for autonomous navigation to achieve sustainable mobility of self-driving vehicles in urban areas and smart traffic control in extra-urban areas*
- ✓ *Technologies to improve energy autonomy and resilience to imperfect communications in situations realistically encountered in application scenarios*
- ✓ *Technologies to reduce the ecological trace of robotic systems by developing new forms of energy and environmentally friendly materials*

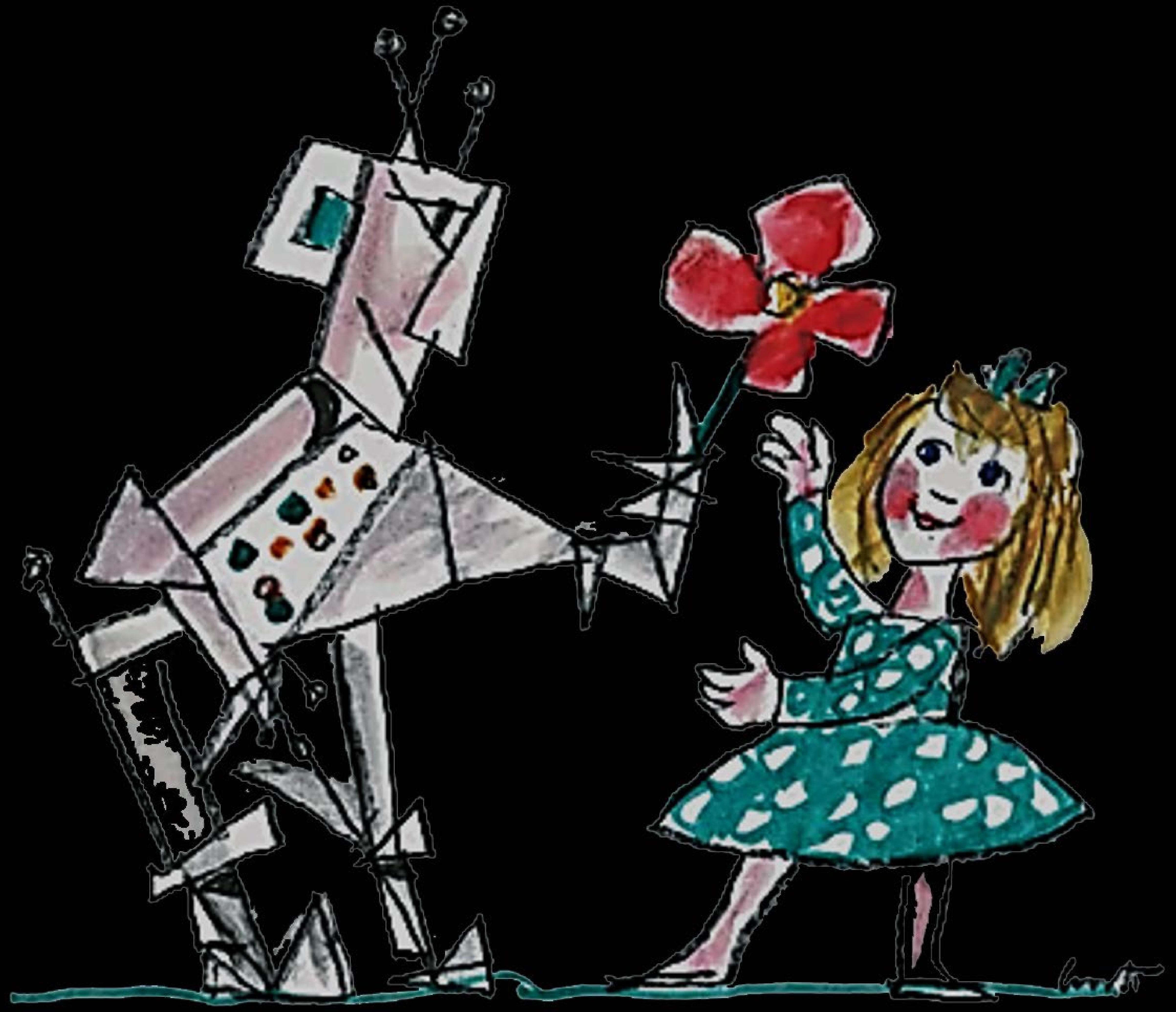
Looking Ahead

The use of AI-empowered robotics aimed at sustainability can help us fight climate change and lead us towards a better future

Levels of Autonomy



Roboethics



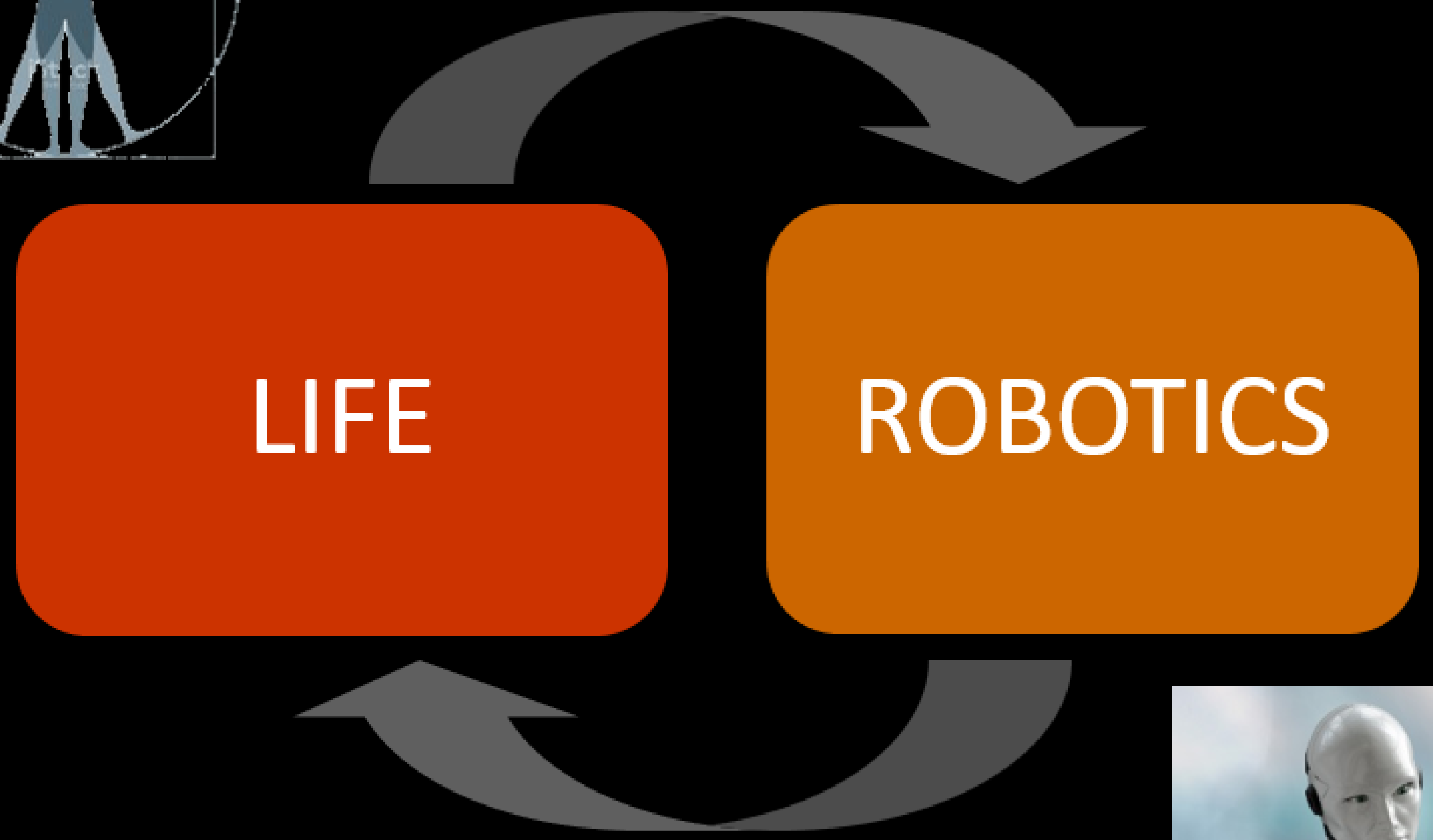
Ethical, legal, societal and economic (ELSE) issues for design, construction and use of robots

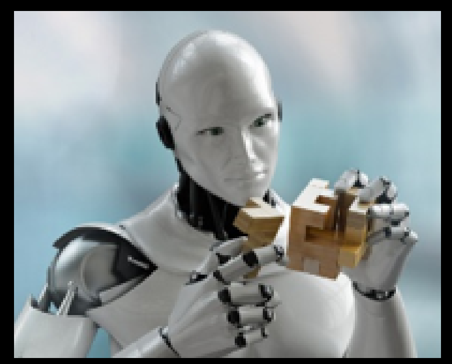
Cohabitation of humans with robots

Fundamental human rights and the moral duties corresponding to them

Robots & Humans

«La scienza m'interessa proprio nel mio sforzo per uscire da una conoscenza antropomorfa; ma allo stesso tempo sono convinto che la nostra immaginazione non possa essere che antropomorfa» *Italo Calvino*





A future where robots are more social than solitary (robot companion)

Robots will enhance human work and life rather than replace us in our homes, hospitals, factories, farms and freeways

Biological inspiration in design and learning from nature (biomimicry and bionics)

Miroka robot by Enchanted Tools

Challenges and Outreach

New emerging areas

Biomechanics
Haptics
Neurosciences
Machine learning
Virtual prototyping
Animation
Surgery
Sensor networks
…

New communities of users and developers

Most striking advances happening at intersection of disciplines

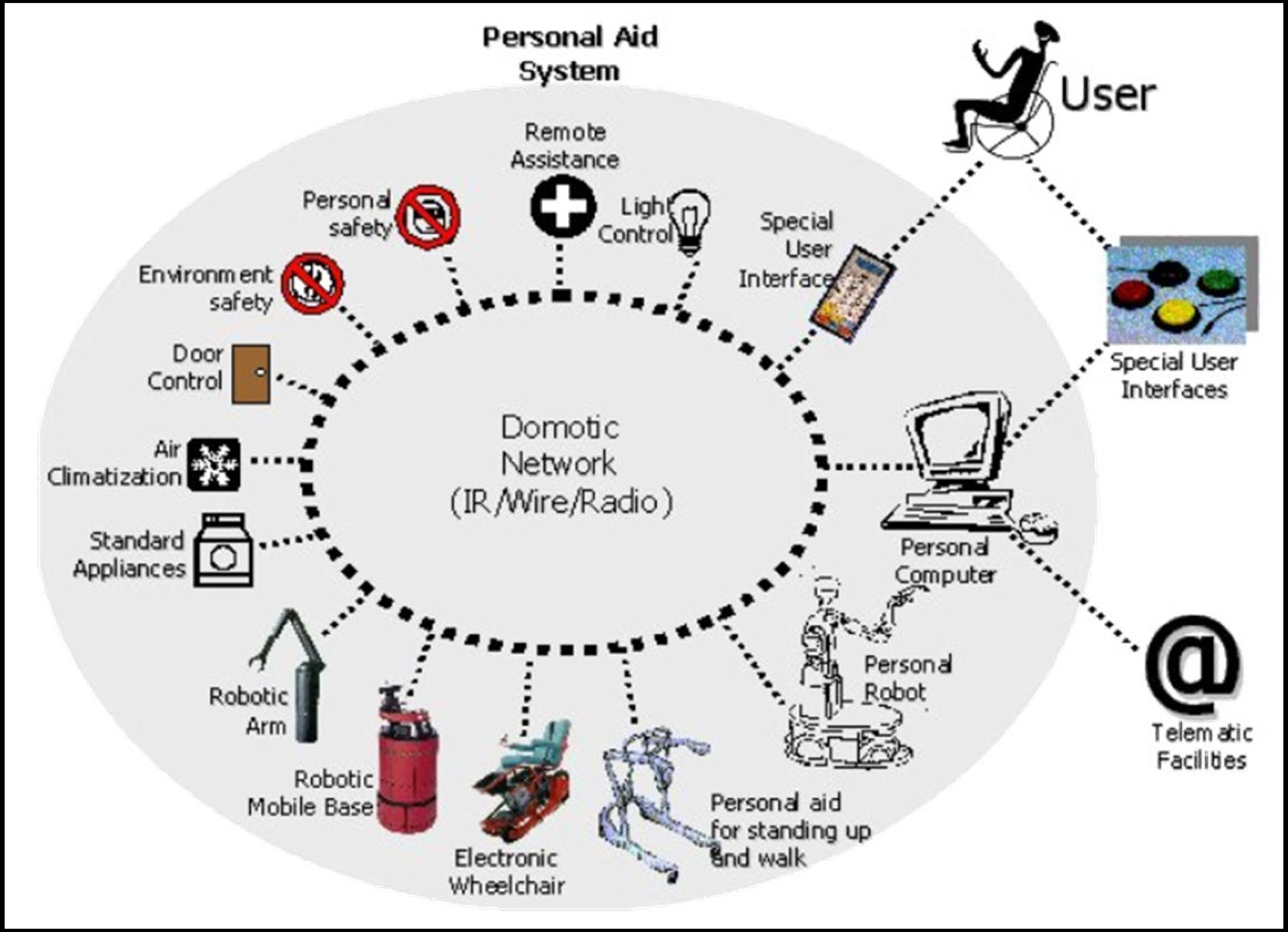
Future developments and expected growth of field largely depending on scientific cooperation

Robotics technology becoming ubiquitous, distributed and embedded into smart environments

Ubiquity & Pervasivity

Integration of robotics, telematics & domotics

Smart environments



Towards a Technological Humanism

«In effetti l'uomo si dimostra essere cosa divina perché dove la natura finisce di produrre le sue spetie l'uomo quivi comincia colle cose naturali a fare coll'aiutorio d'essa natura infinite spetie» *Leonardo da Vinci*

«A distanza di 100 anni dall'ingresso della parola robot nel nostro lessico, la sfida e allo stesso tempo l'opportunità che il mondo della ricerca dovrà rappresentare è relativa a futuri scenari in cui la robotica diventerà un mezzo interattivo per contribuire a migliorare le condizioni di vita. In questa visione, la rivoluzione dei robot potrà aiutarci a riaffermare la caratteristica meno artificiale del nostro mondo: la nostra umanità»

Atlante Treccani, Bruno Siciliano (2020)

Robotics @ PRISMA Lab

- 3 Full Profs + 3 Associate Profs + 4 Assistant Profs
- 19 Research assistants + 9 PhDs + 9 Support staff
- 25 EU projects in last 18 years (incl. 2 ERC Grants)
- Partnership w/ 180 foreign institutions & companies
- 10 Patents + 35 Awards in last 20 years
- Research areas
  - Aerial Robotics
  - AI & Cognitive Robotics
  - Dynamic Manipulation & Legged Robotics
  - Human–Robot Interaction
  - Industrial Robotics
  - Medical Robotics
- Start-ups
  - Neabotics
  - Herobots

https://prisma.dieti.unina.it

https://www.icaros.unina.it

Neabotics Service Robotics Solutions

HEROBOTS

Our EU Research Projects

RoDyMan
SAPHARI
PHRIENDS
DEXMART
REFILLS
Harmony
ENDO THERANOSTICS

Manipulation & Interaction

AIRobots
AEROARMS
AERIAL-CORE
SHERPA
ARCAS
HYFLIERS
AERO TRAIN

Aerial Robotics

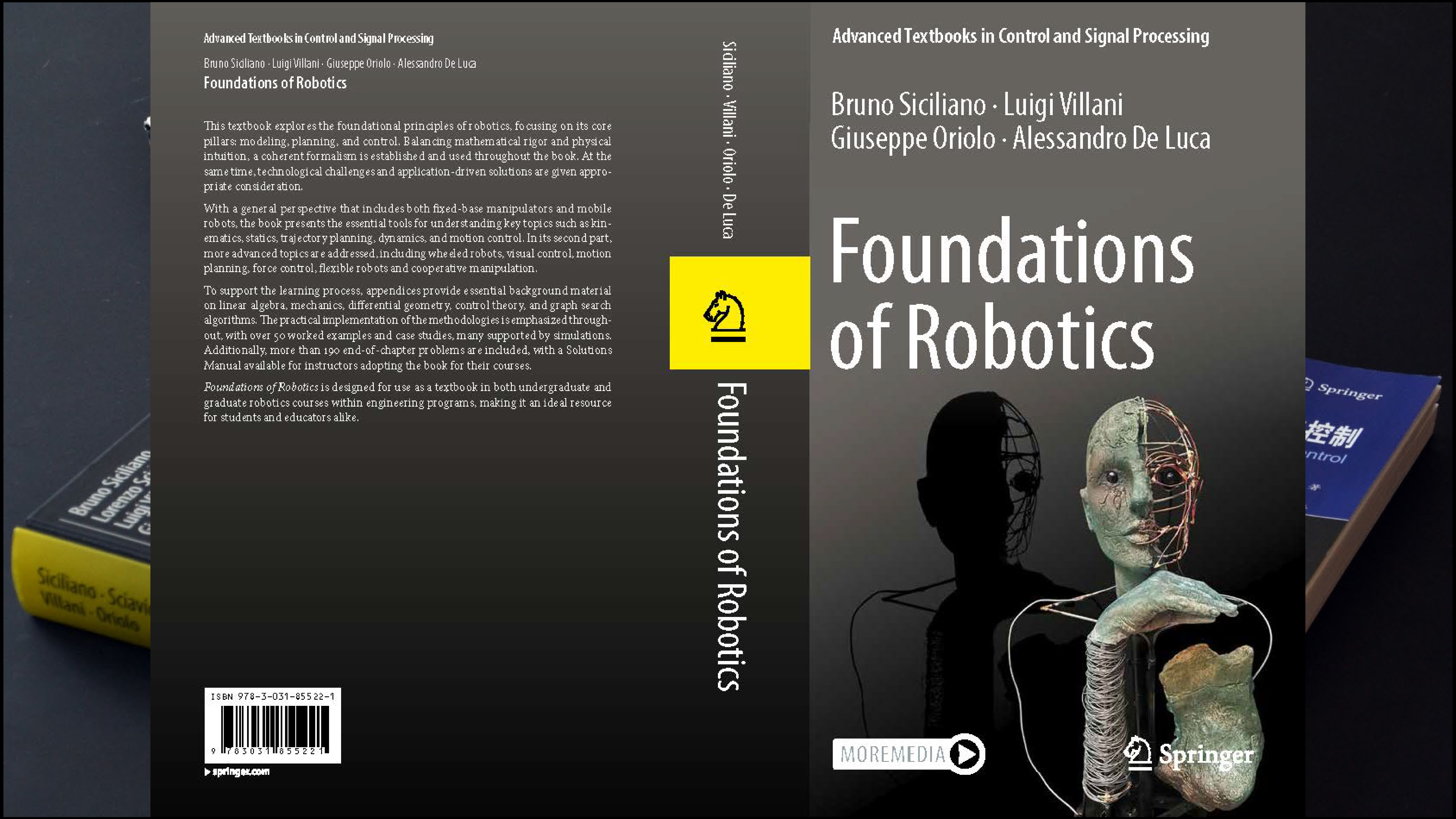
European ROBOTICS Research Network EURON
ROCK eu
ROCK eu²
eu Robotics
ethicbots
ECHORD
European Robotics Challenges
euROBIN
RIMA
DIH²

Networking & Technology Transfer

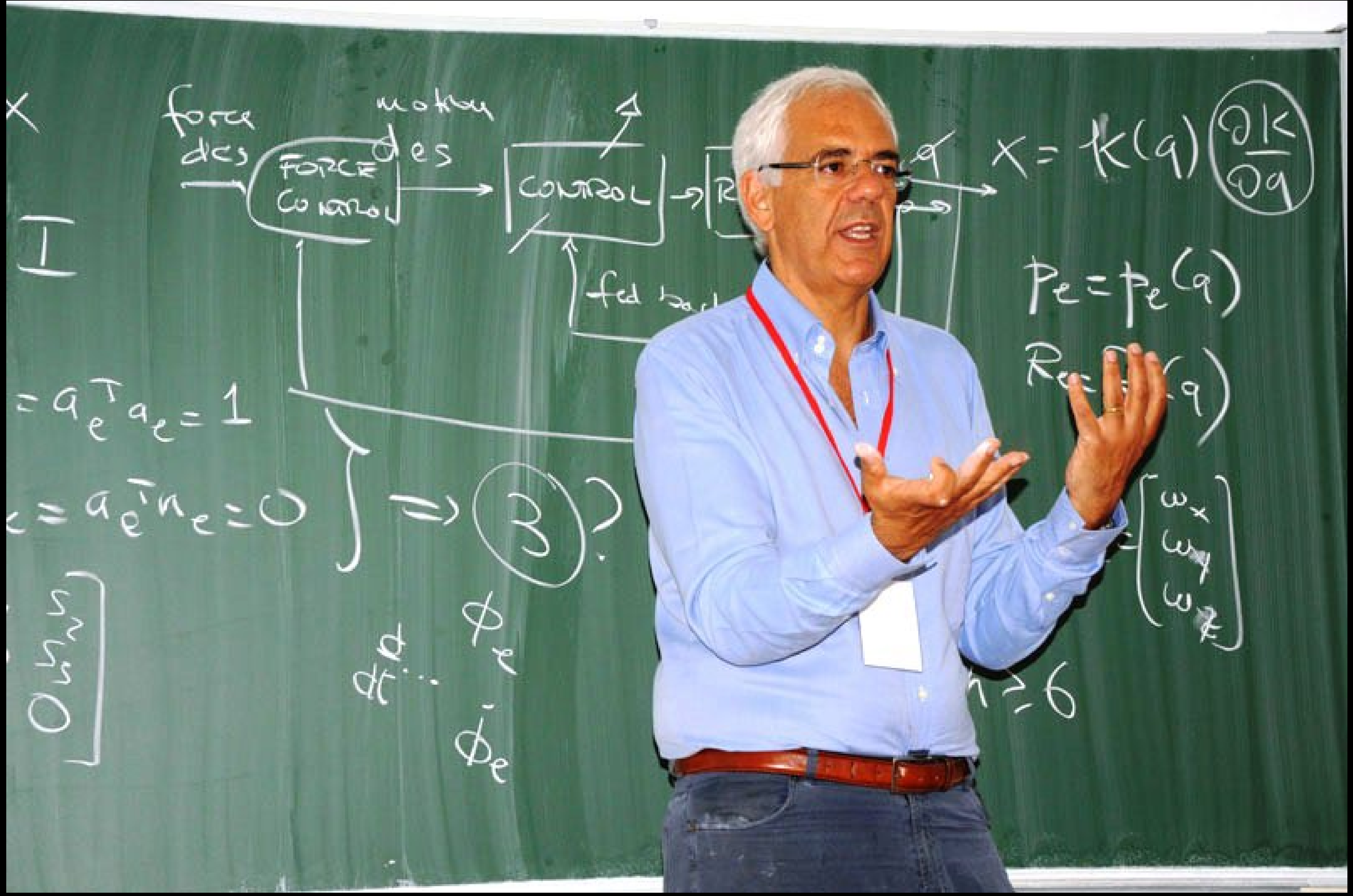
prisma LAB

Robotics Goes PRISMA

The Textbook



A New Learning & Teaching Environment: The MOOCs

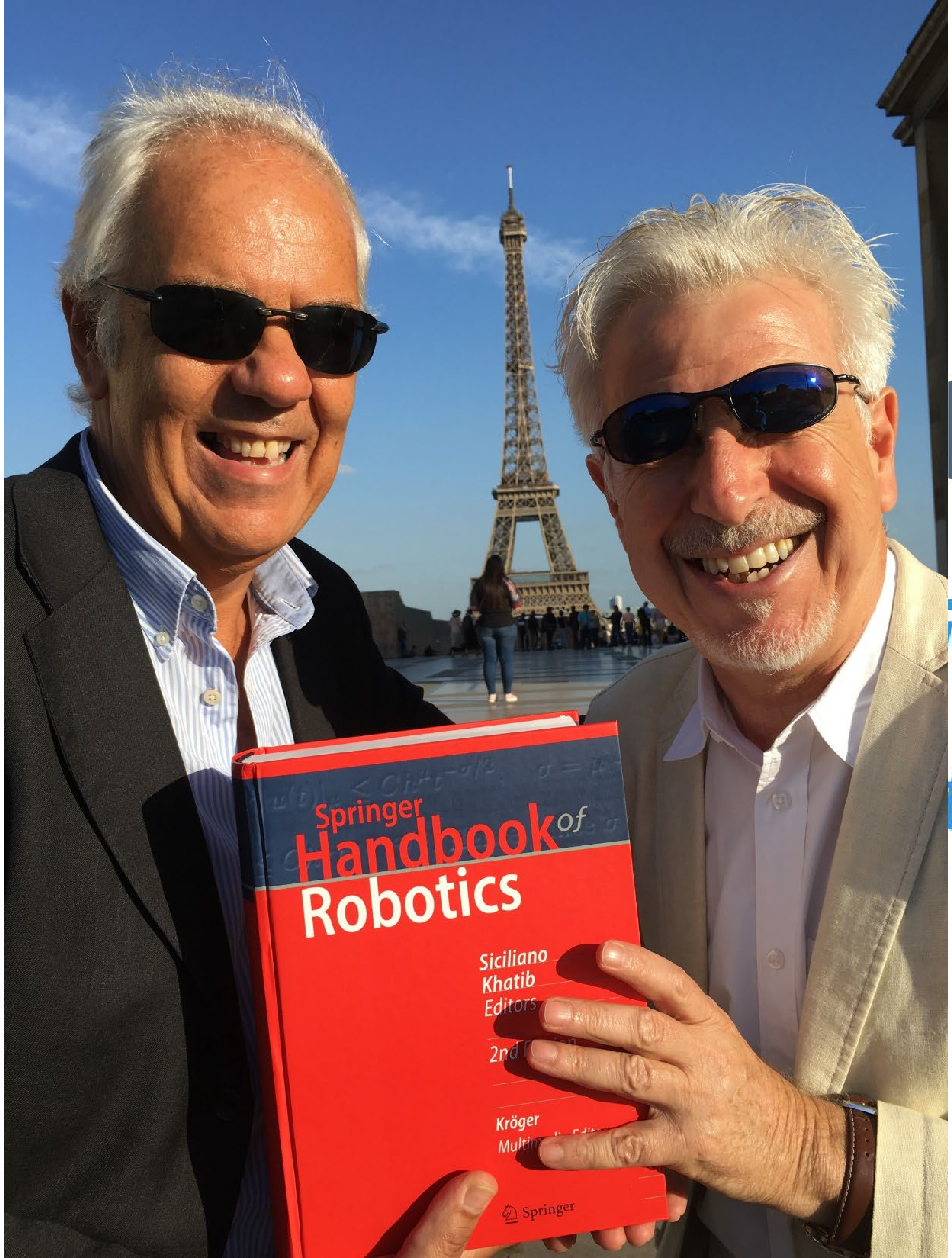


- ✓ *Teaching is pure adrenaline*
- ✓ *Robotics is highly interdisciplinary*
- ✓ *Generations of students learning robotics from my textbook*

After 25 years of lectures ex cathedra …

- ✓ *Speaking towards the infinite*
- ✓ *No need to provide complementary material, as that is available on the net*
- ✓ *My video lectures are the glue to the technical contents of the slides*

✓ *Available on edX*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Handbook of
Robotics
Siciliano
Khatib
Editors
Kröger
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ian

tor:


Imagine
Robotics


Bruno Siciliano
Editor
Robotics Goes MOOC
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