Introduction to Robotics

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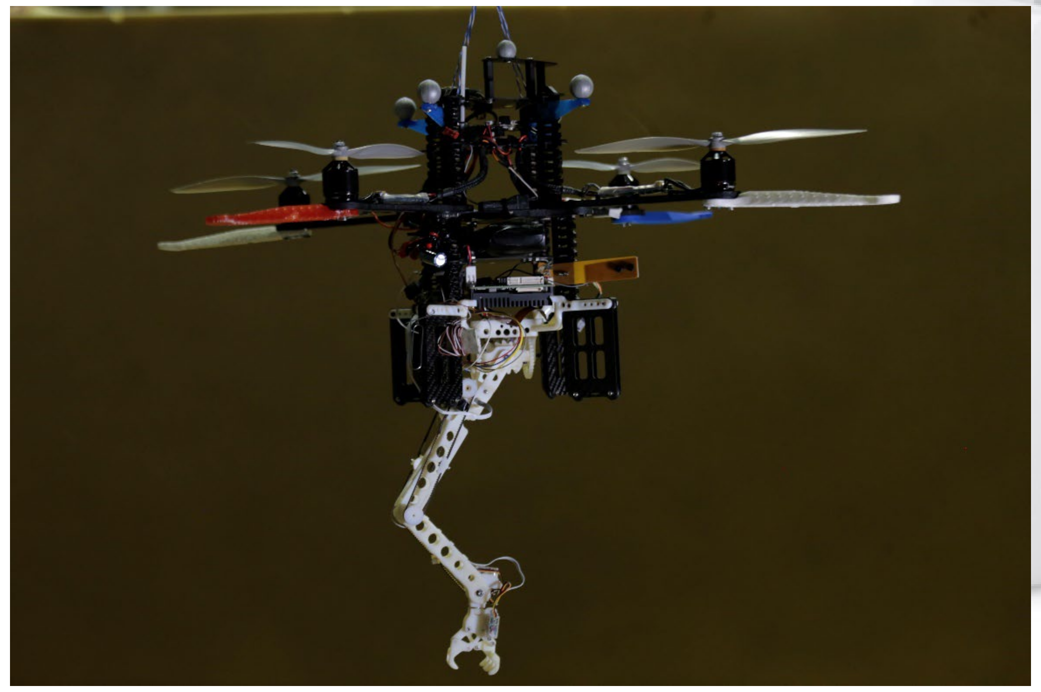
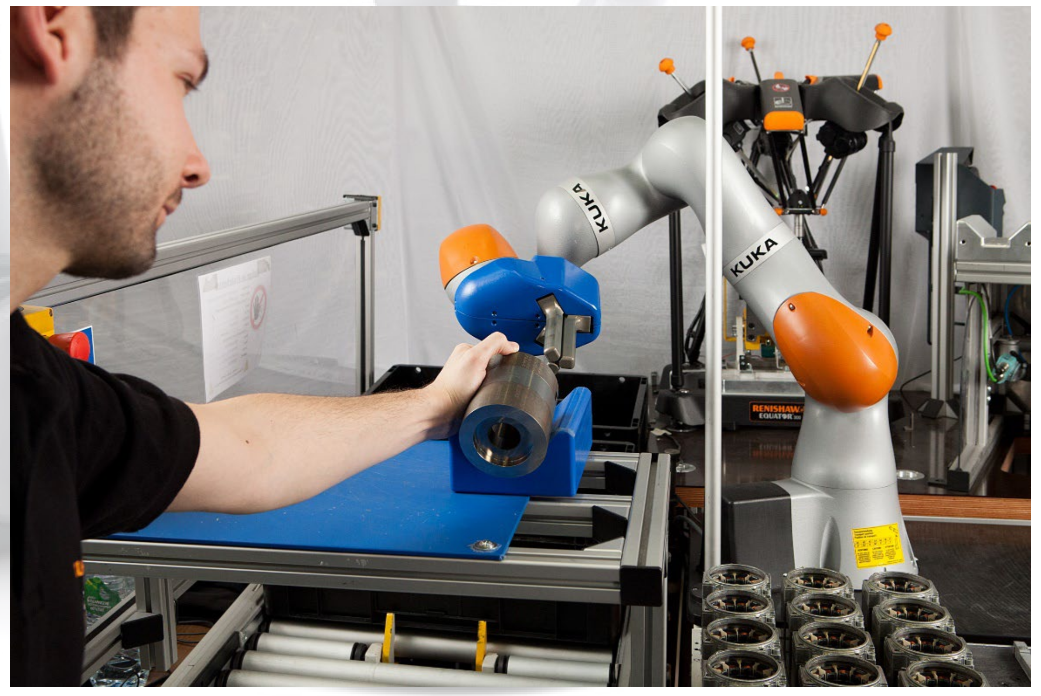
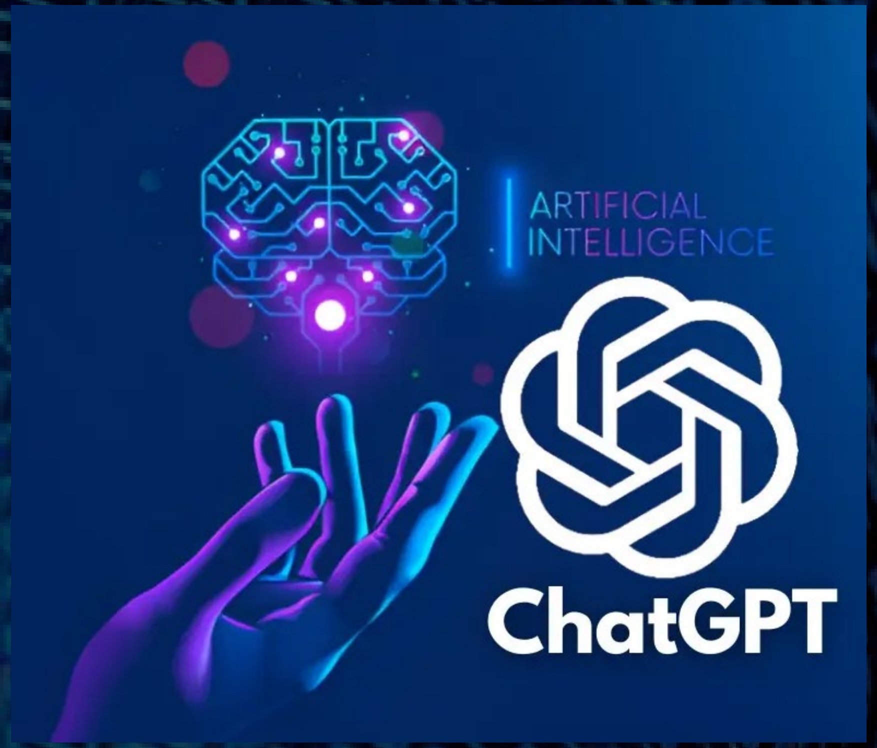
robot





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

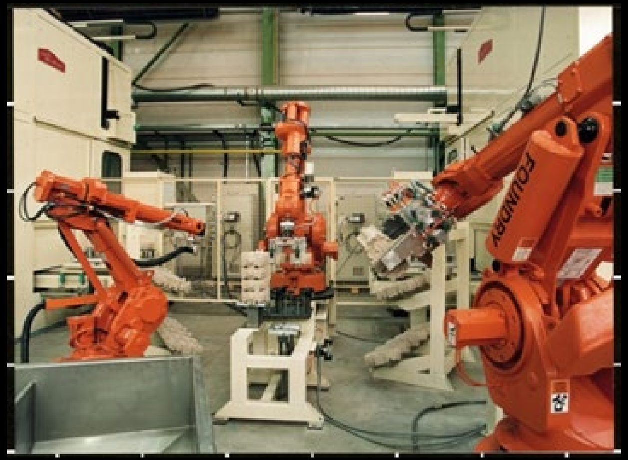
Humans' DREAM of replicating themselves

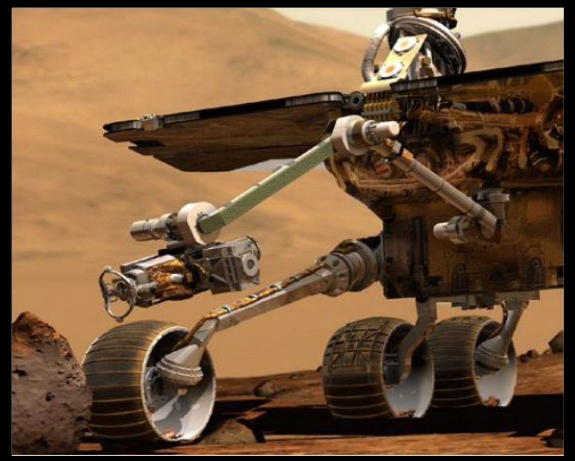
NEED for useful machines

industrial robotics

1960-1980

manufacturing applications





field robotics

1980-2000

space applications

service robotics

2000-2020

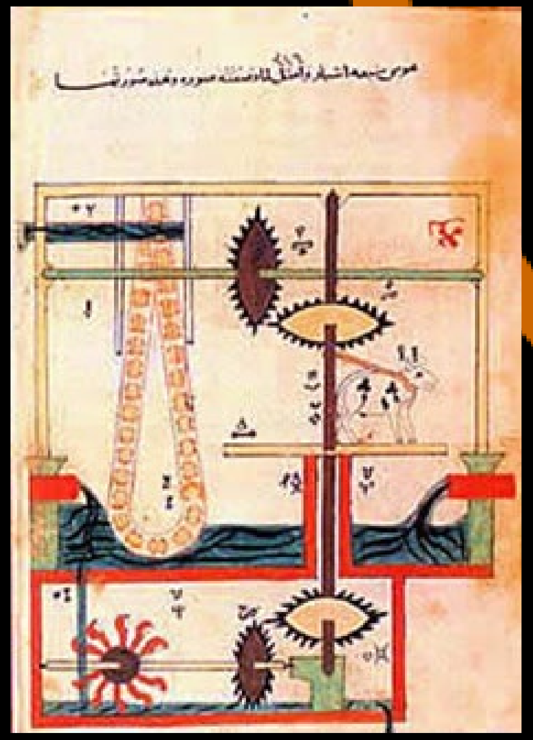
medical applications

2020-2040

personal robotics

humanoid robotics

?



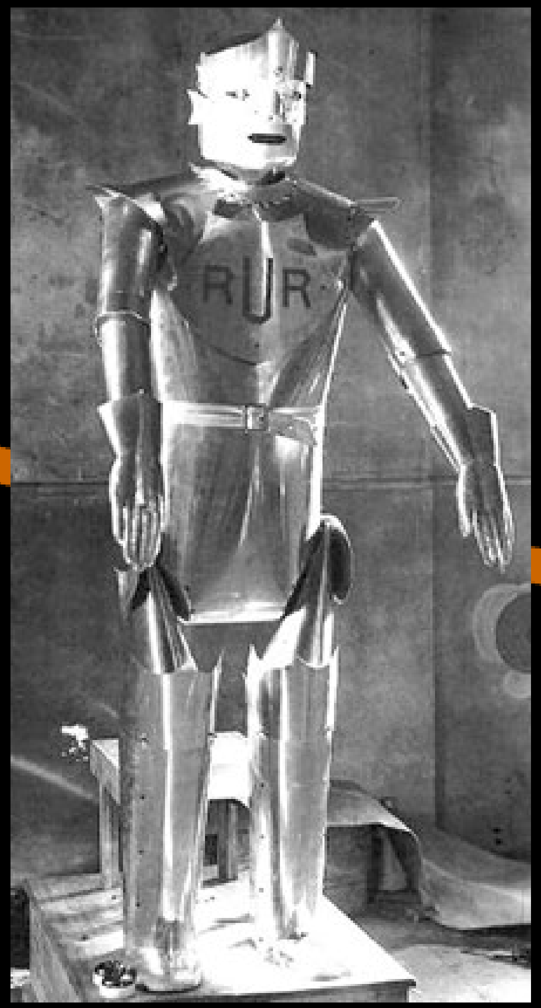
1200

1500

1550

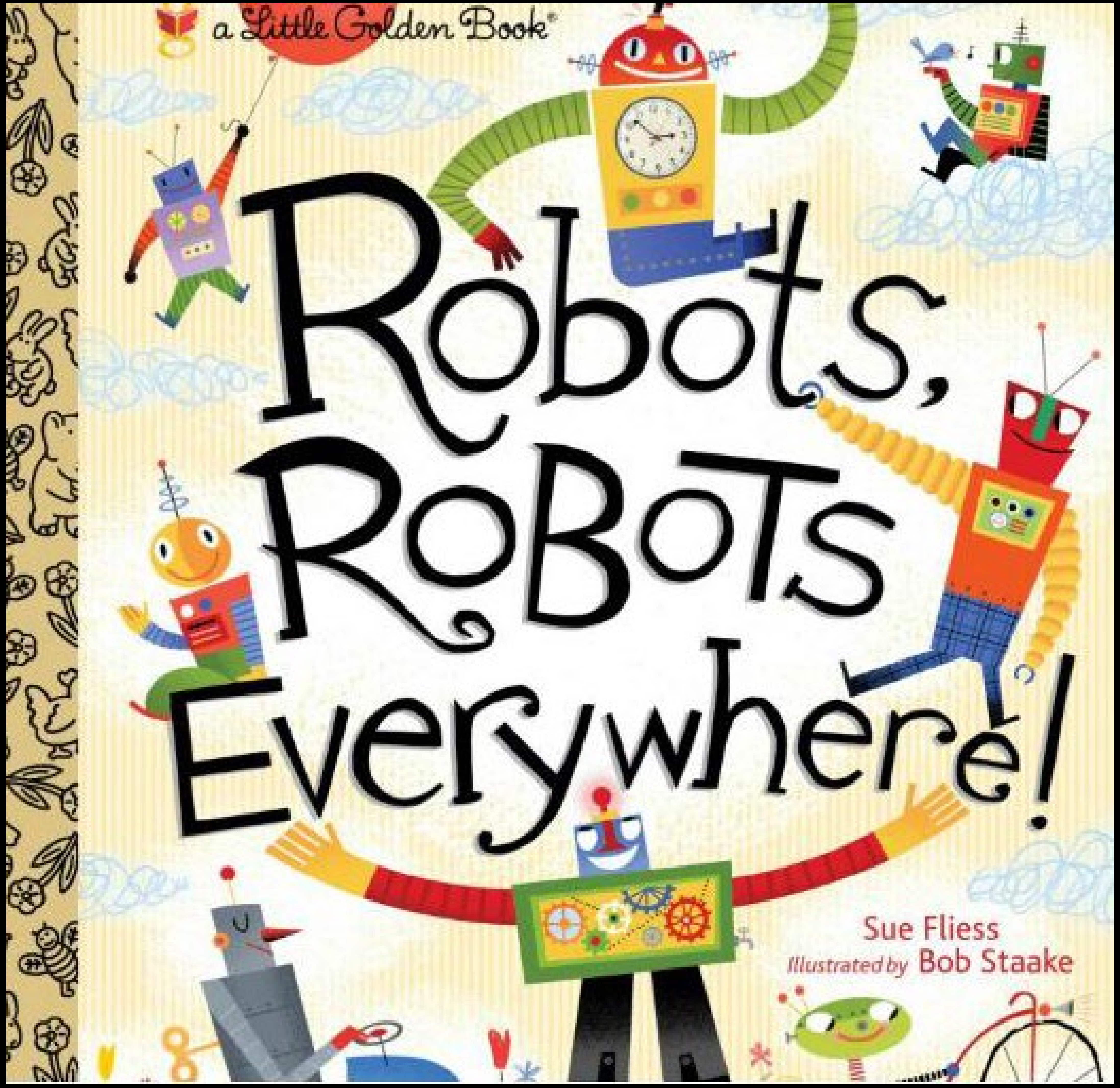
1750

1920



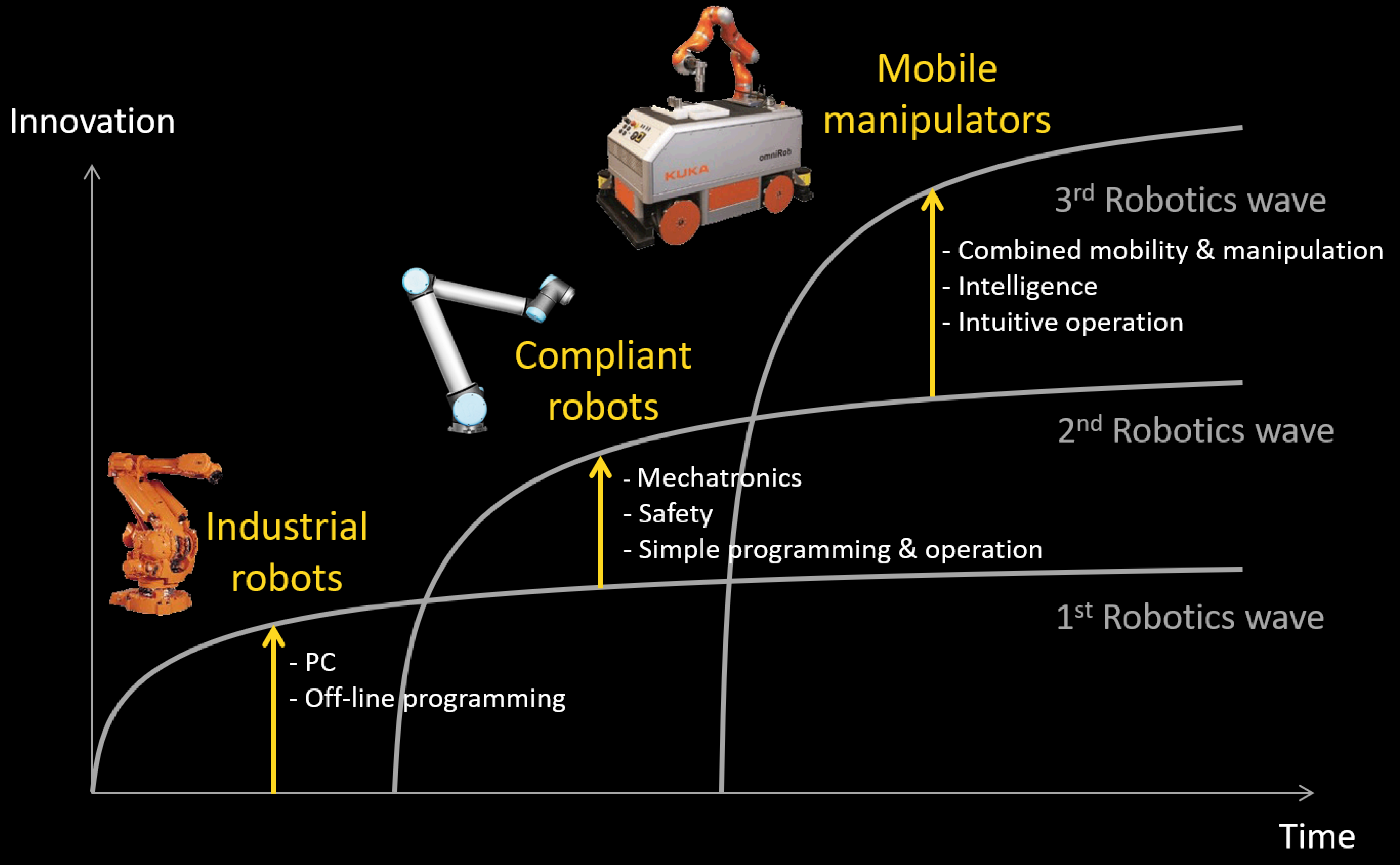
2005

The Age of Robots



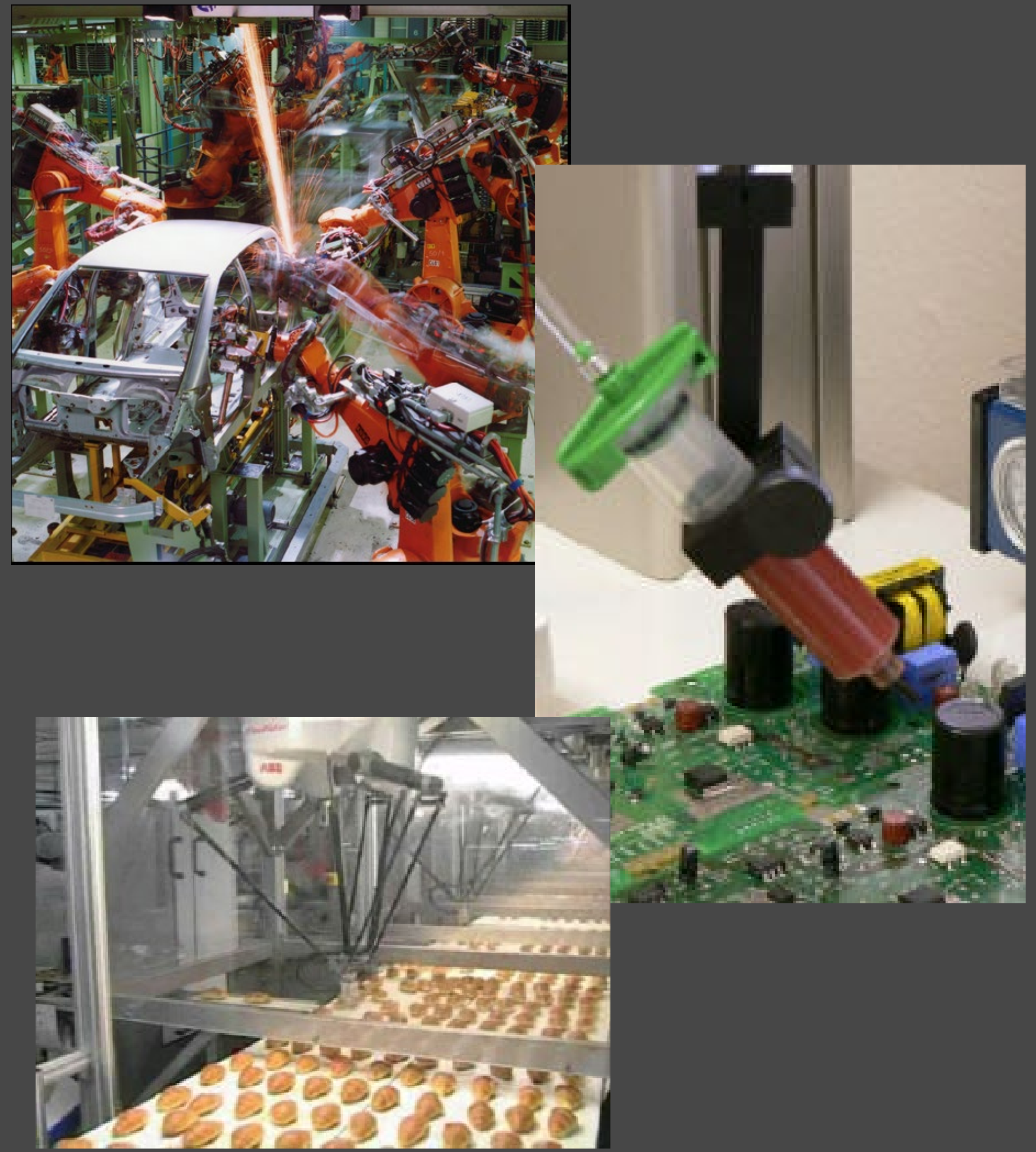

robots are
with us
within us
among us
Photo © Sam Ogden

Industrial Robotics Evolution



Robots in Industry

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

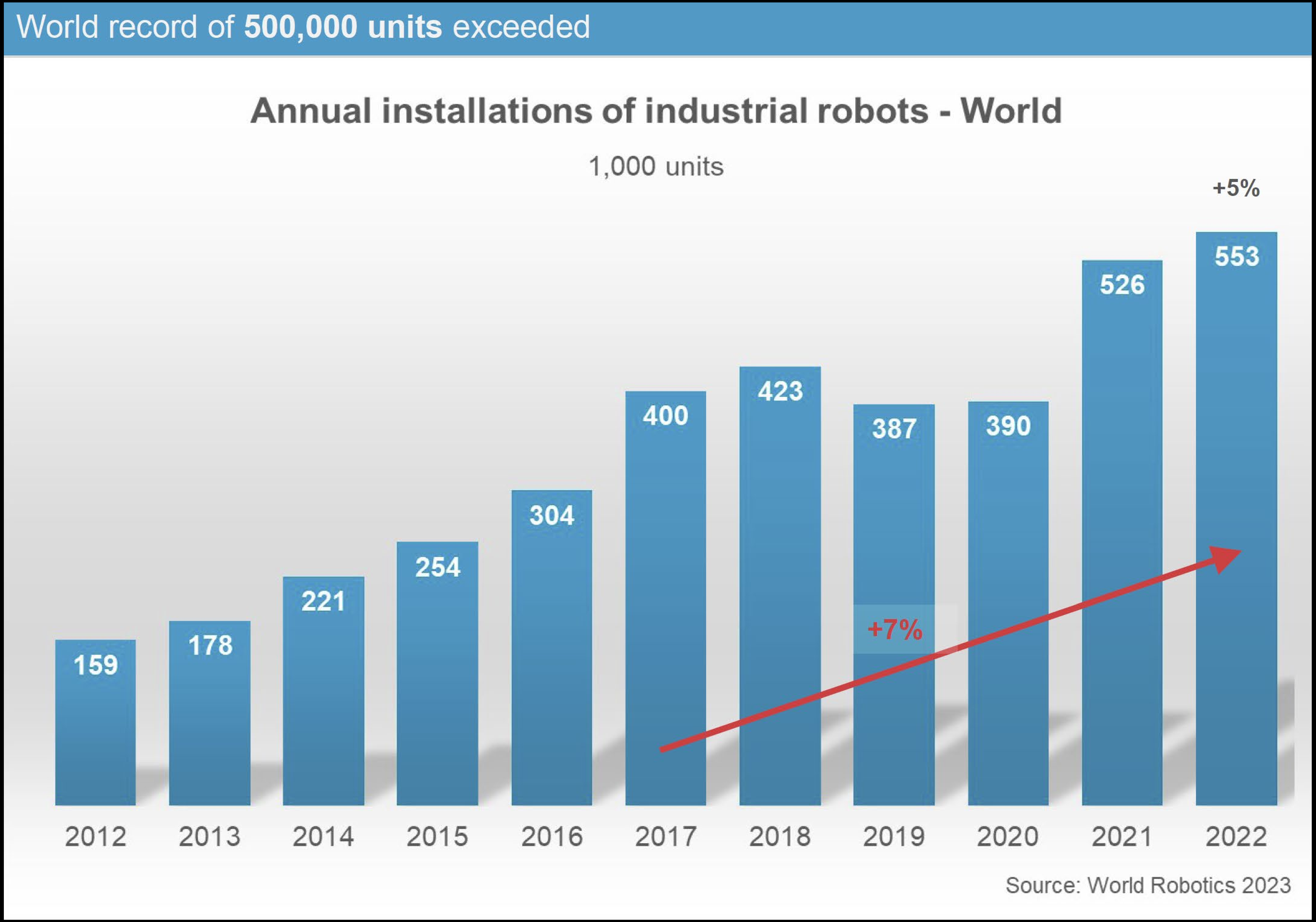
https://ifr.org

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

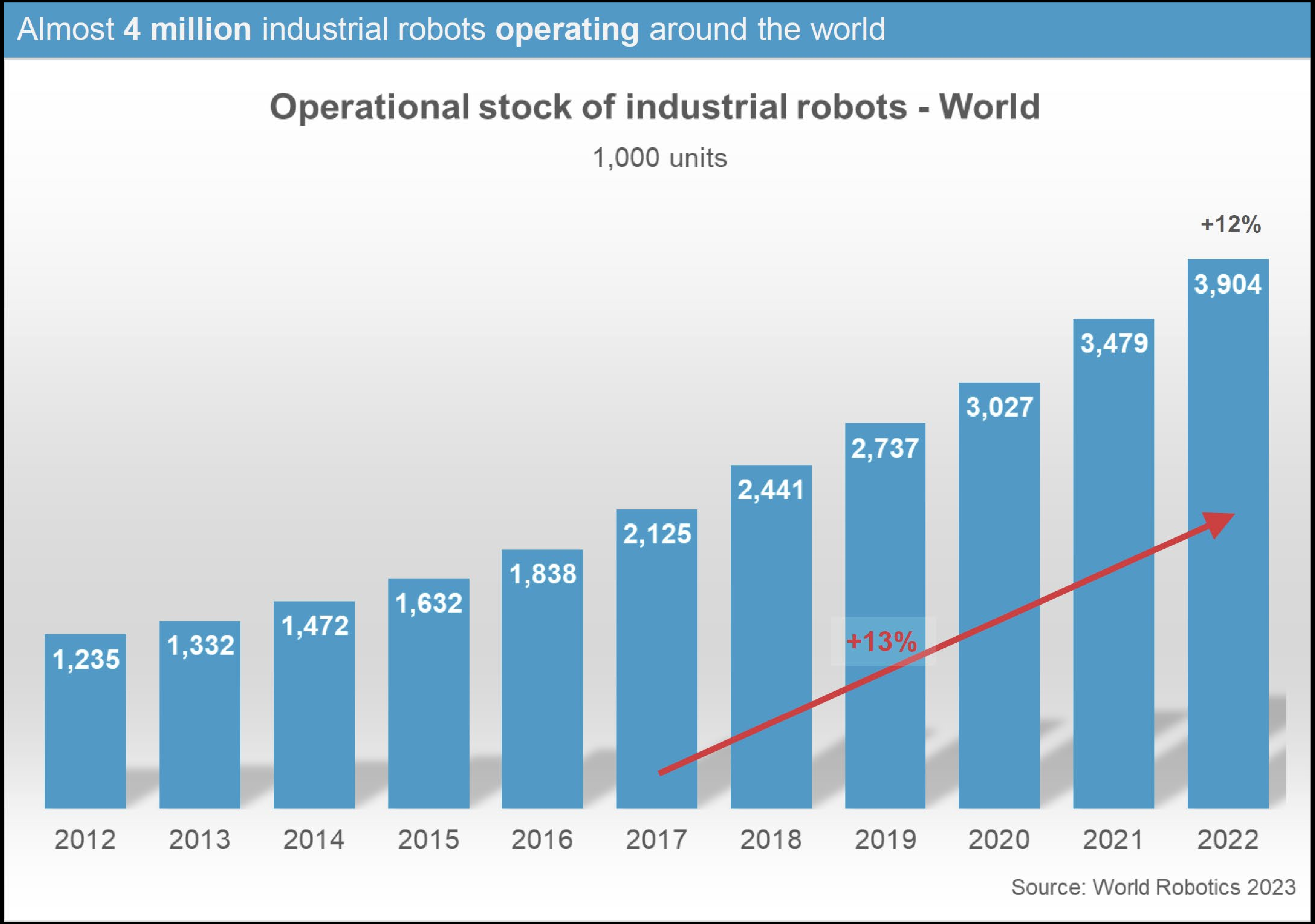
Industrial Robots

- ✓ *3.9 million of robots @ work worldwide (+12%), CAGR 2017–2022 +13%*
- ✓ *553.000 new installation in 2022 (+5%), CAGR 2017–2022 +7%*
- ✓ *Largest markets: China, Japan, USA, Korea, Germany, Italy (91%)*

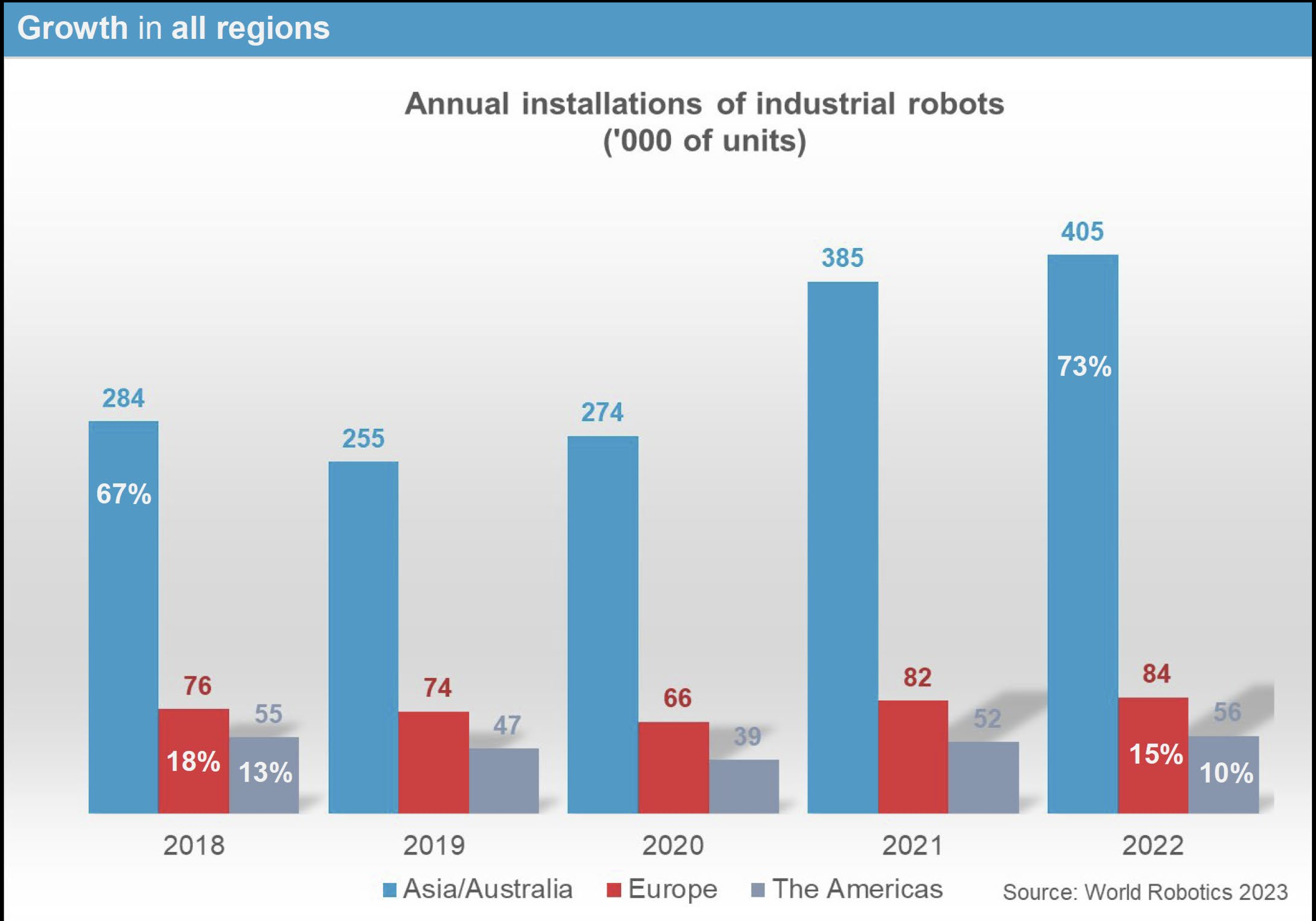
Annual Installations



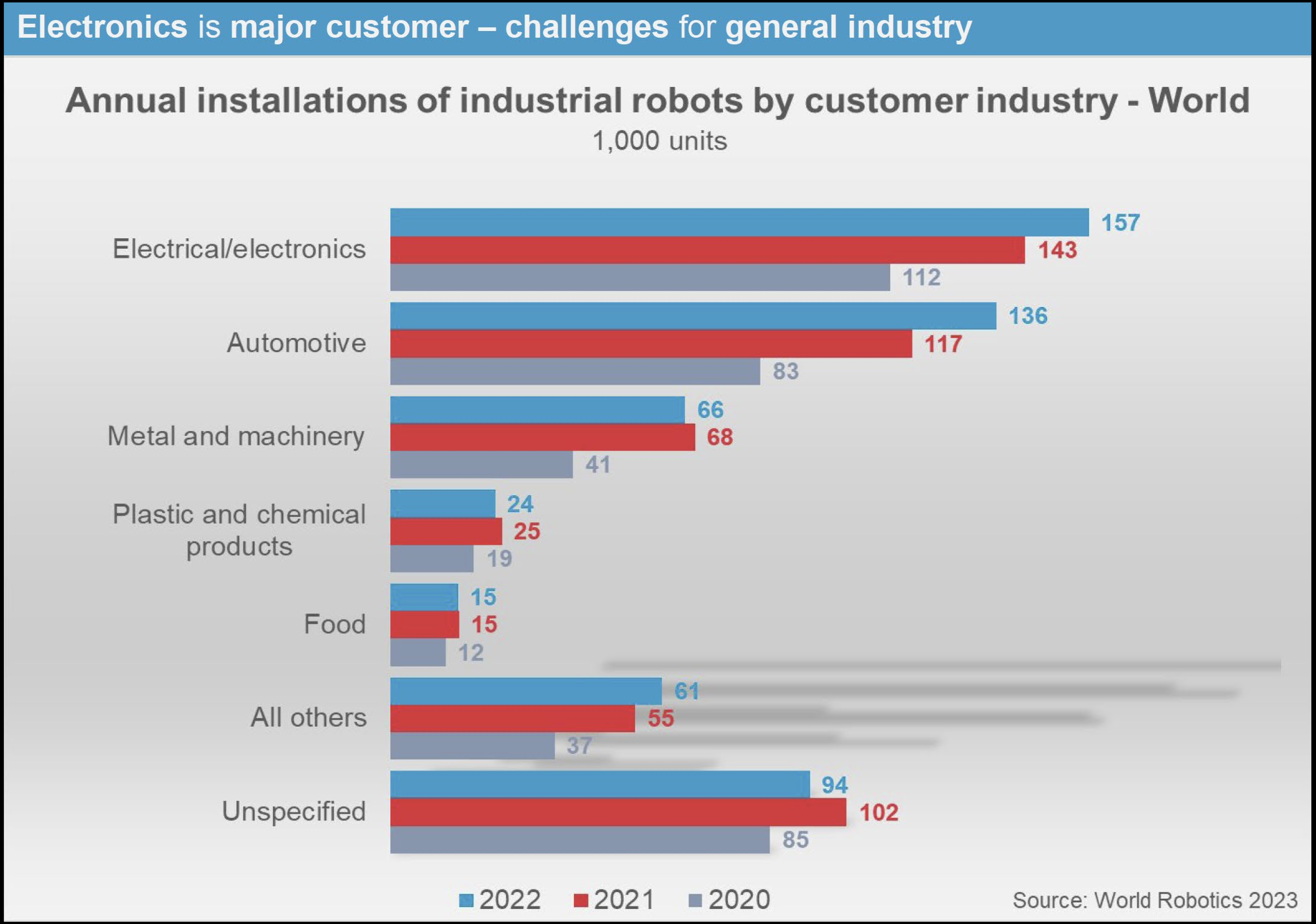
Operational Stock



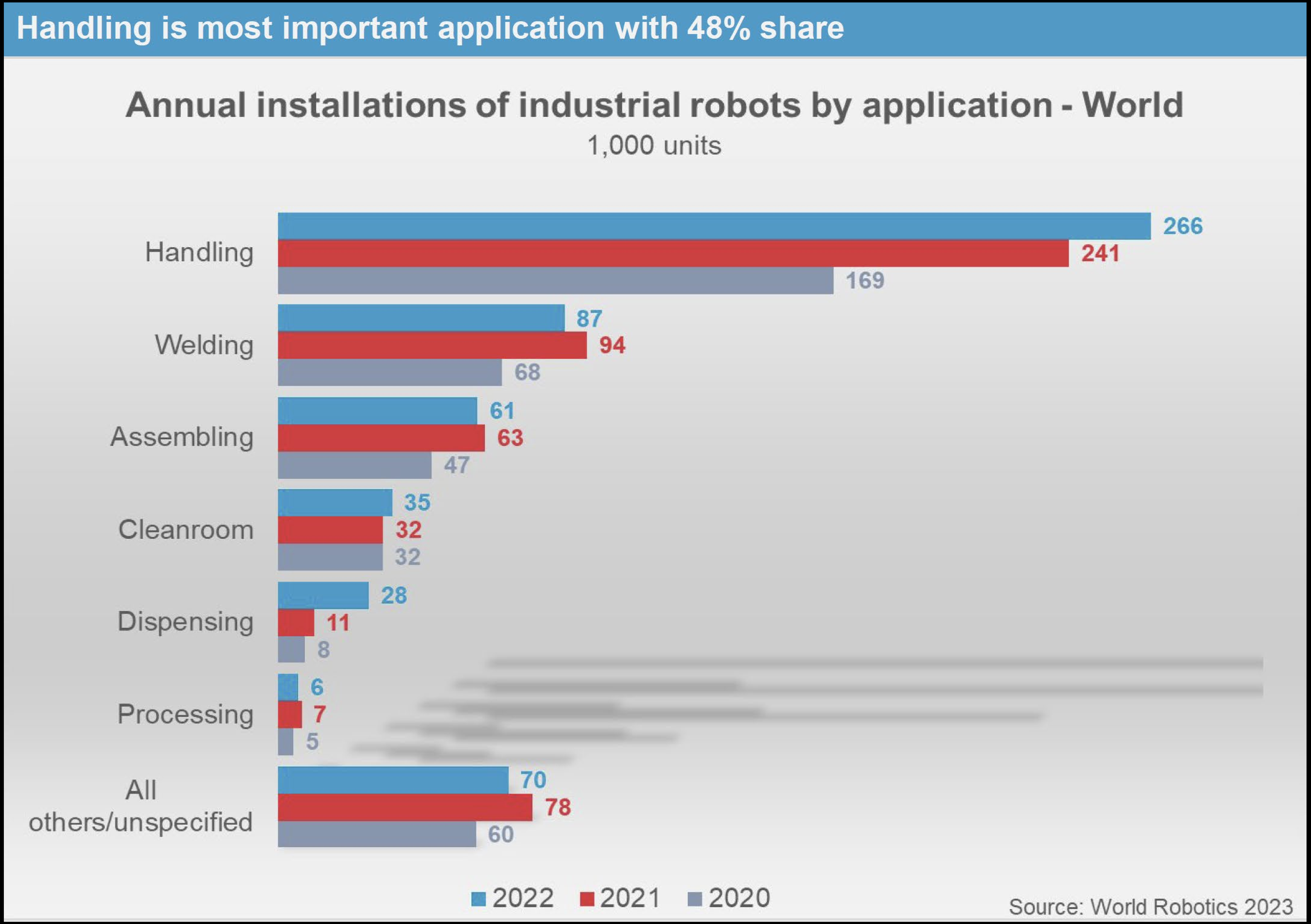
Geographical Regions



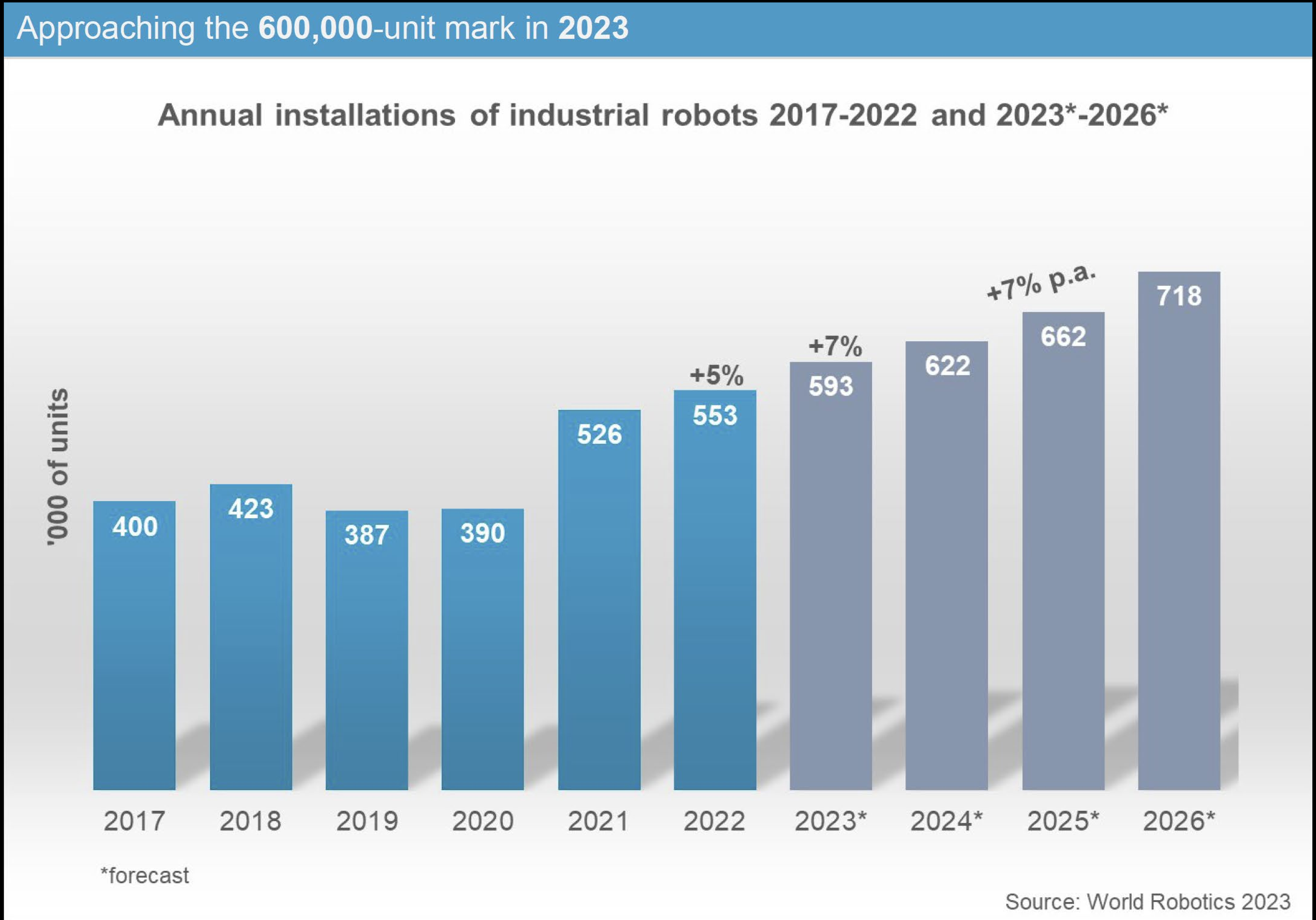
Customer Industries



Applications



Forecast


Approaching the 600,000-unit mark in 2023
Annual installations of industrial robots 2017-2022 and 2023*-2026*
'000 of units
400
423
387
390
526
553
593
622
662
718
+5%
+7%
+7% p.a.
2017
2018
2019
2020
2021
2022
2023*
2024*
2025*
2026*
*forecast
Source: World Robotics 2023

Short-Term Market Determinants

Supply chain constraints are easing

Inflation remains high

Slowdown of global economic growth

- ✓ *No direct correlation to robot installations*
- ✓ *Development in China has strong impact on overall performance*

Orders: backlog from 2022 and declining intake in 2023

- ✓ *Orders from 2022 shipped in 2023*
- ✓ *Base effect: strong order intake in 2022*

Technological Trends

Cloud computing and 5G mobile networks

- ✓ *new business models*
- ✓ *optimized performance*
- ✓ *fully digitalized production*

Machine vision

- ✓ *simplifies programming*
- ✓ *detection of shapes and guide grippers in complex environments*

Artificial Intelligence coming to market

- ✓ *smarter, faster, more efficient and more accessible automation*
- ✓ *enhancing maintenance*
- ✓ *faster programming, learning by experience*
- ✓ *supporting sustainability*

Market Trends

Labor scarcity in many developed economies is driving the demand for automation

Reconsideration of supply chains and closeness to customers

- ✓ *Re-and nearshoring of production*

Small and medium sized enterprizes (SMEs) need easy access to automation

- ✓ *"Democratizing" robotics*
- ✓ *Lowering the hurdles for robotization: IFR's Go4 Robotics campaign https://go4robotics.com/*

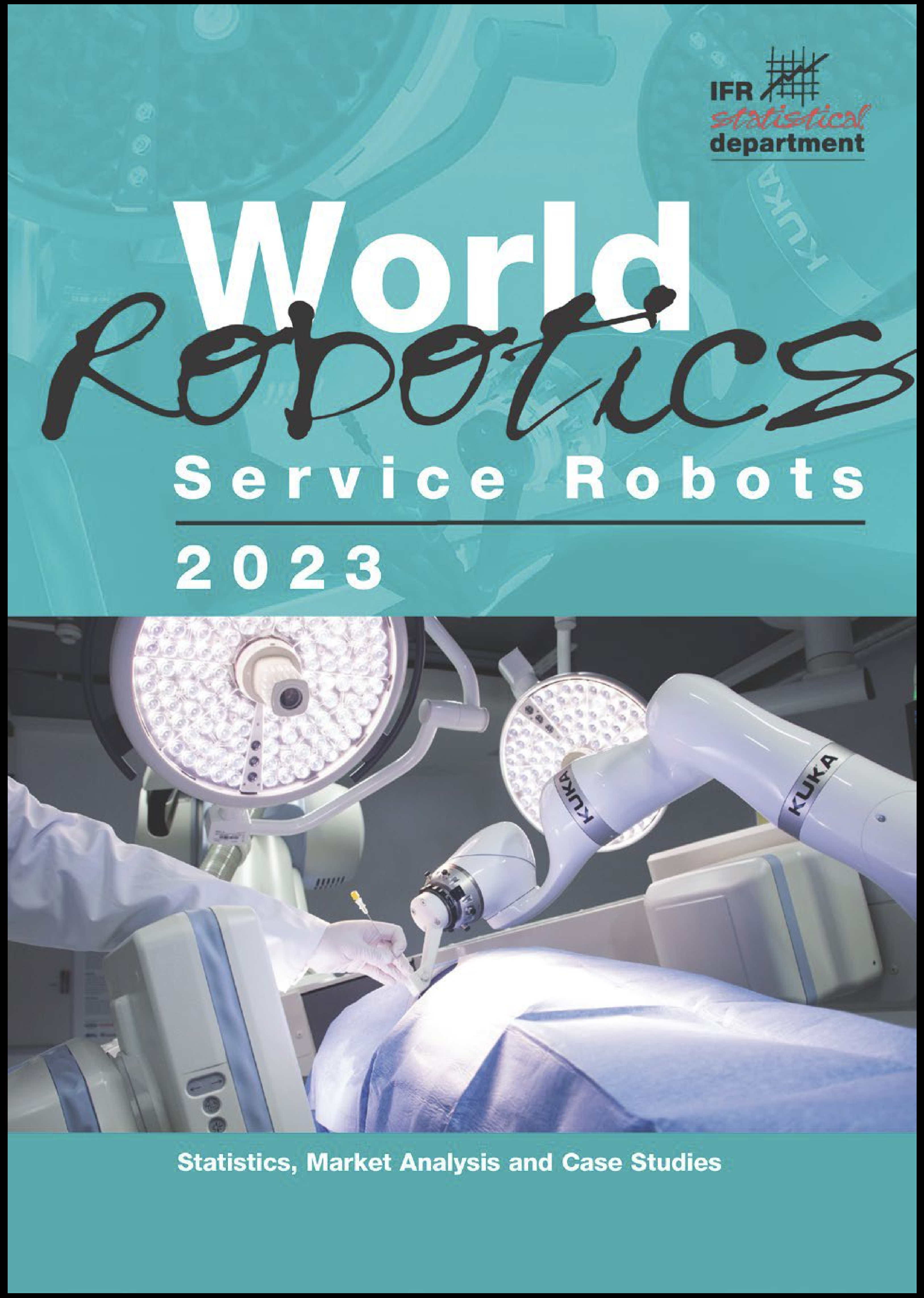
World Statistics

New professional service robots

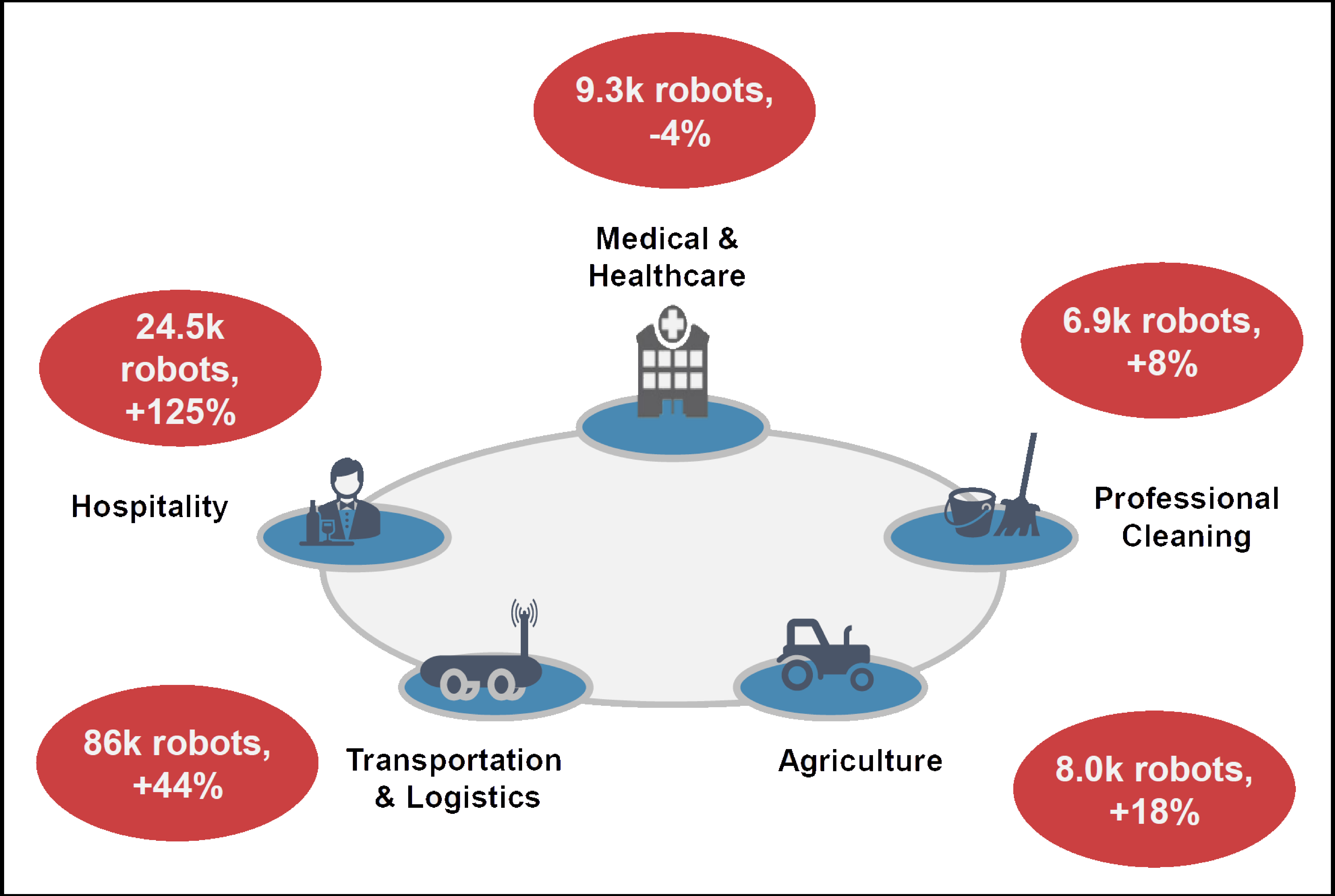
✓ *158,000 units (+48%)*

New consumer service robots

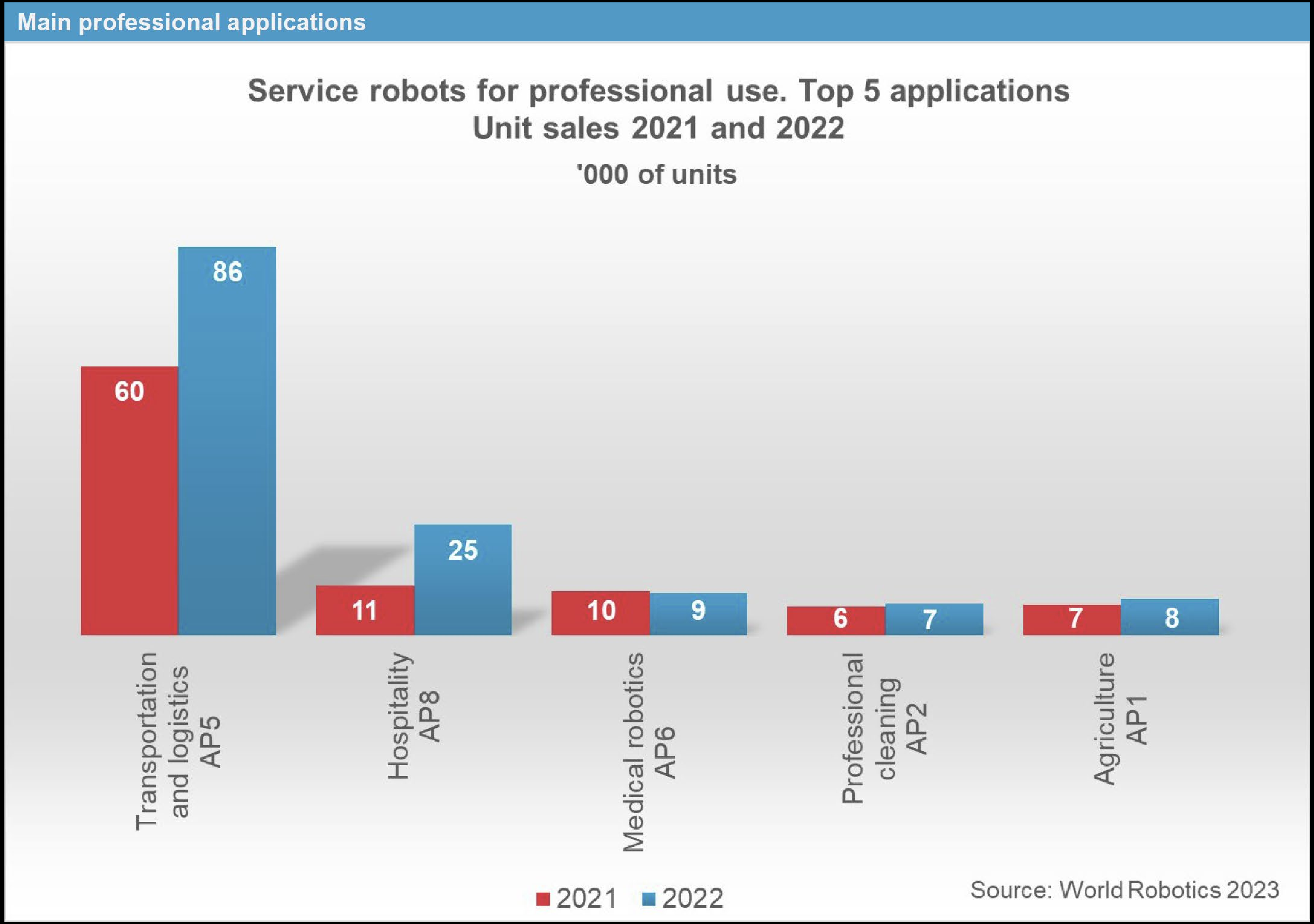
✓ *5 million units (-5%)*



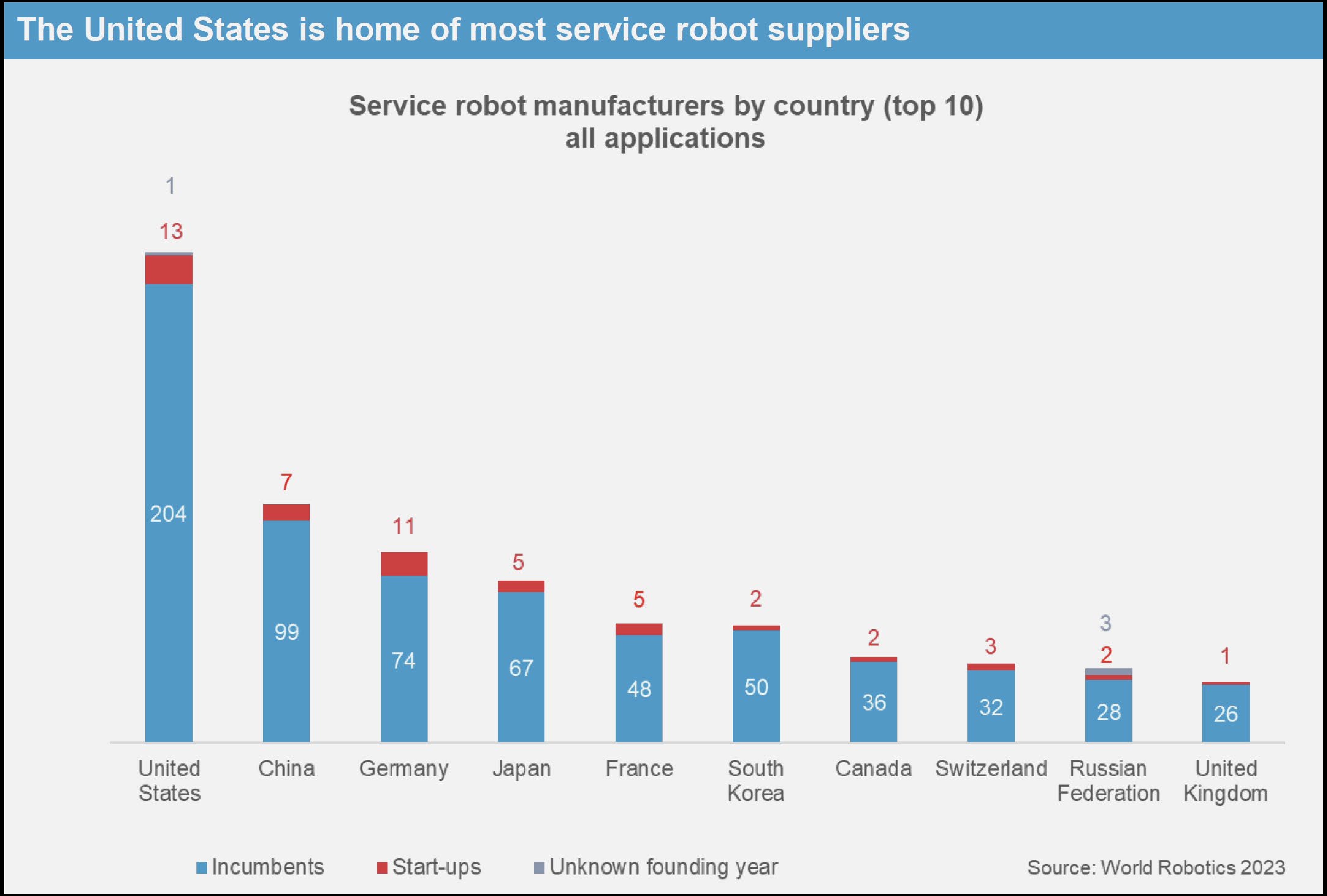
Top 5 Application Areas of Professional Service Robots



Applications

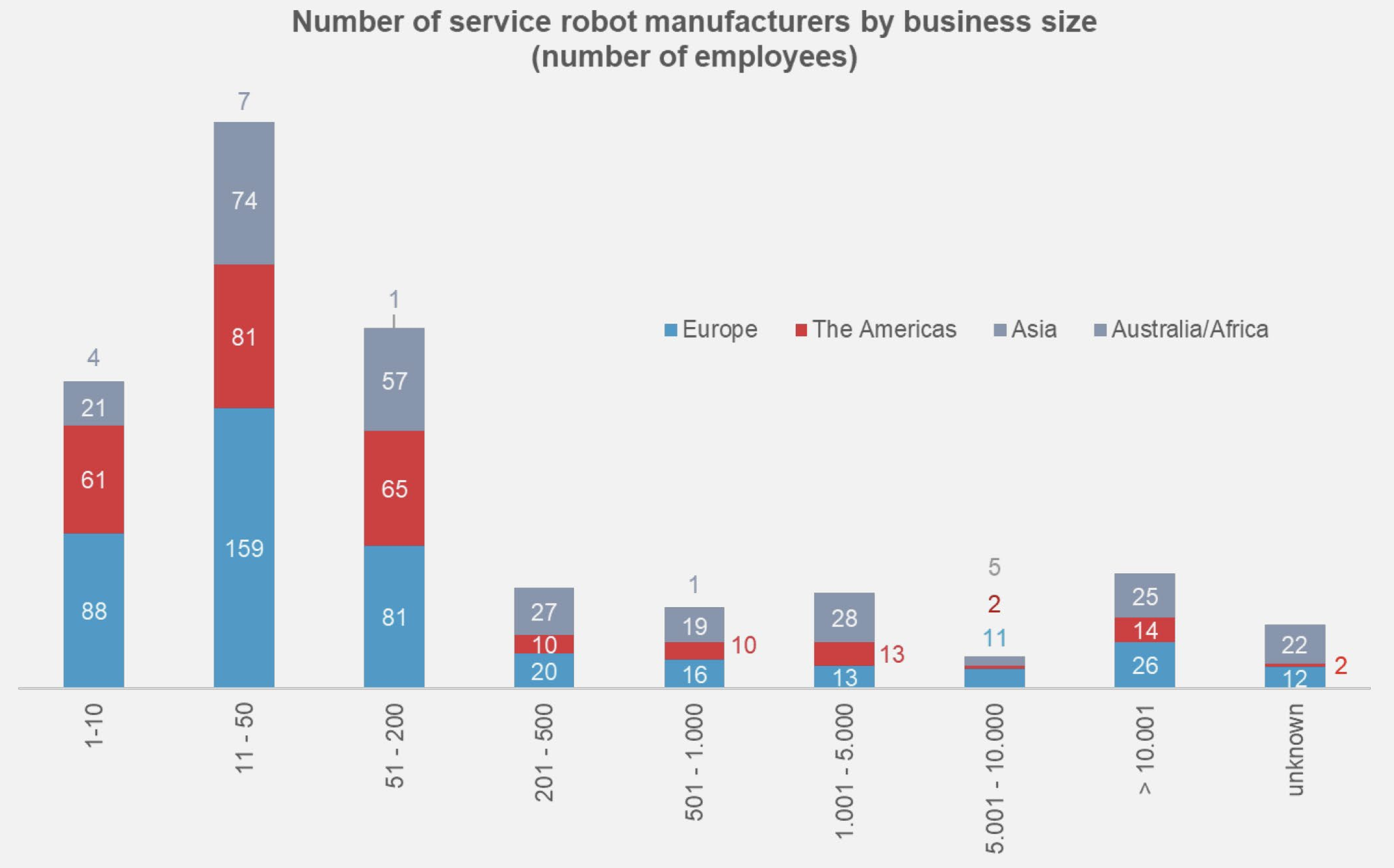


Geographical Regions



Manufacturers by Business Size

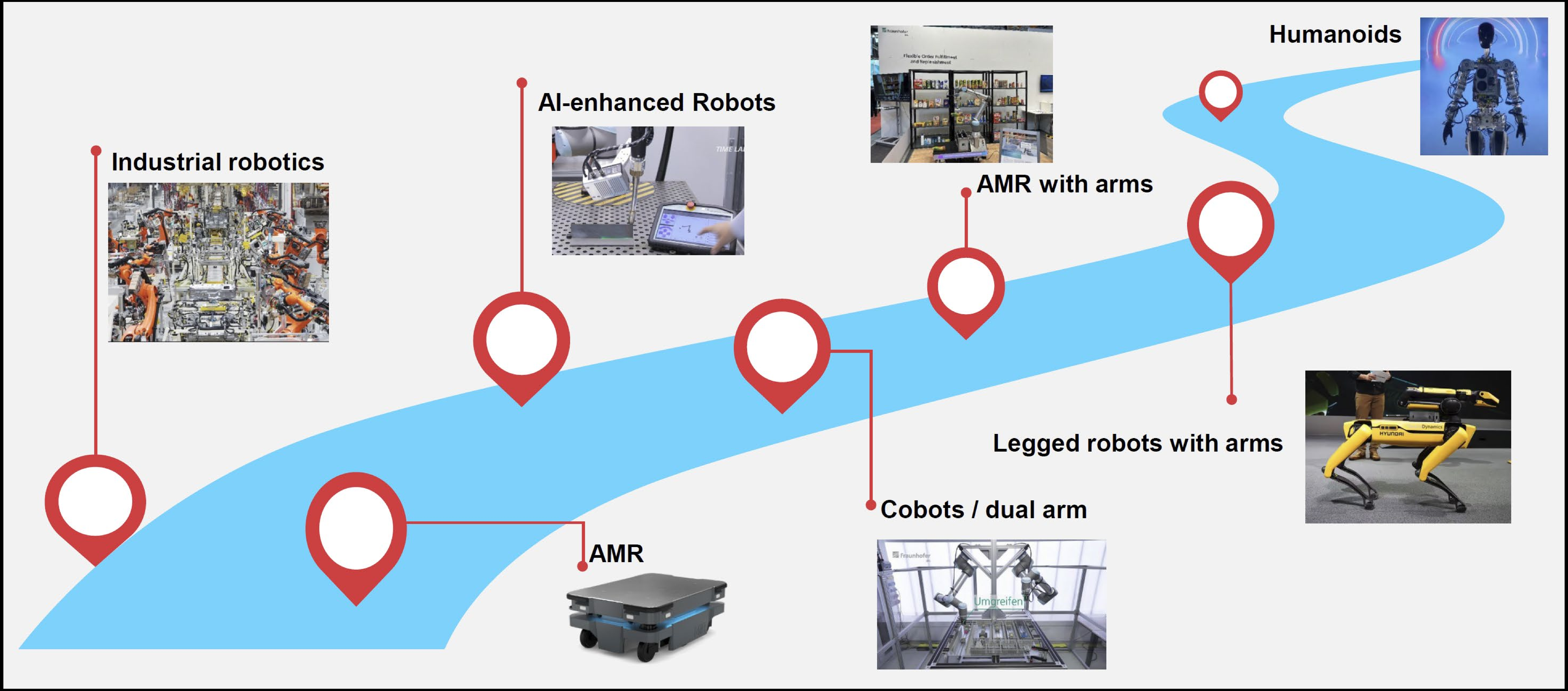
81% of service robot suppliers are small-medium sized enterprises*



*(SME with <=500 employees)

Source: World Robotics 2023

Long-term Research Trends



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)*

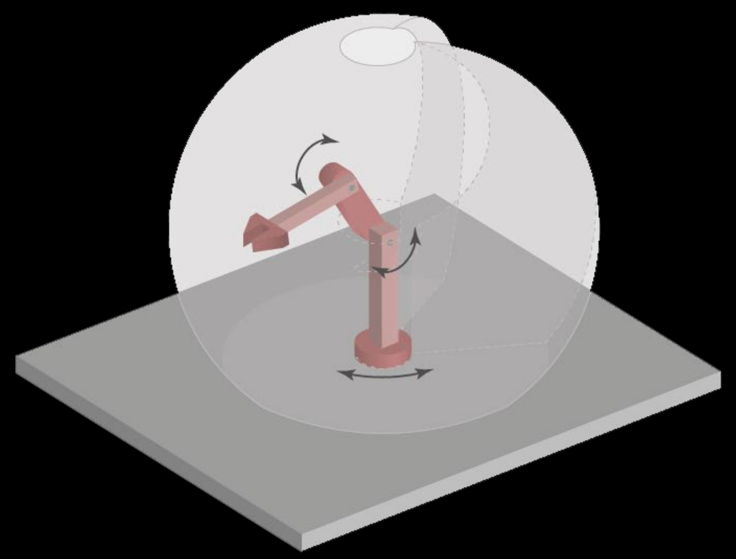
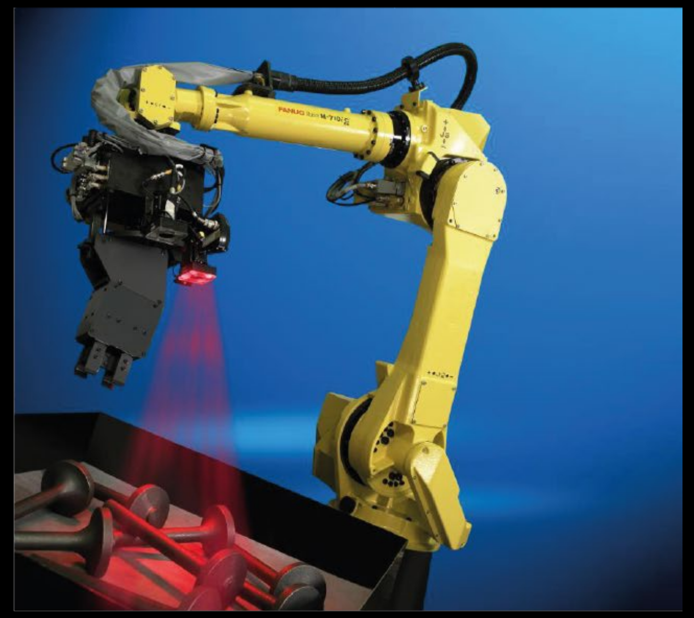
Control system

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

Robot Manipulators

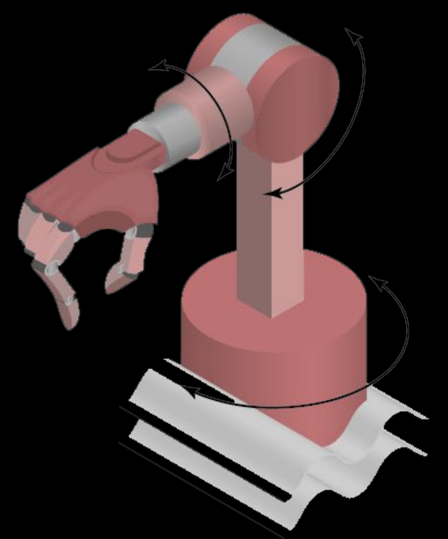
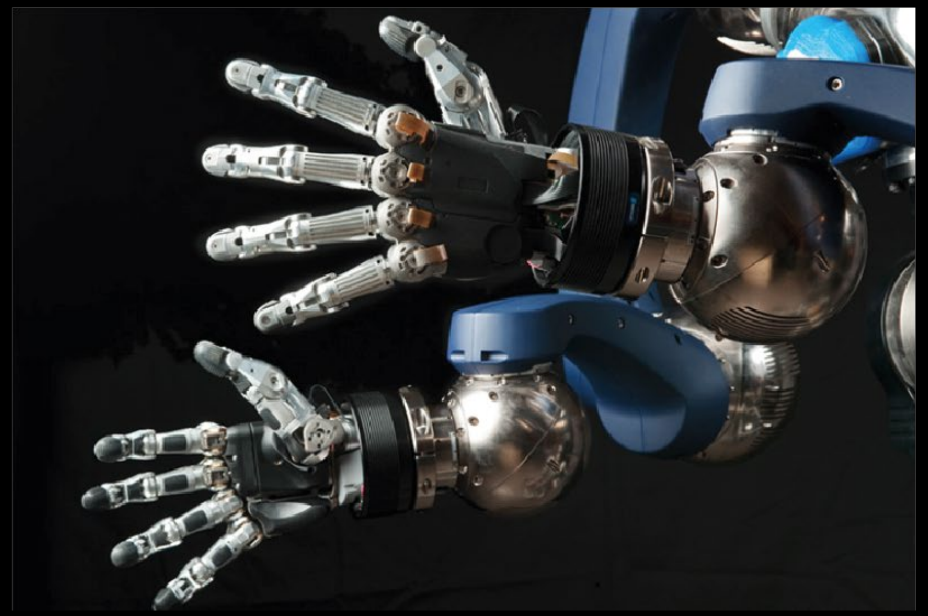
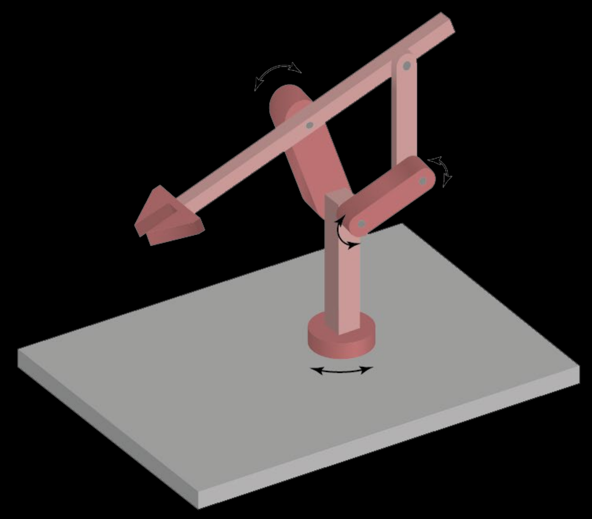
Mechanical structure of robot manipulator: sequence of rigid bodies (links) interconnected by means of articulations (joints)

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

Mechanical structure

- ✓ *Open vs. closed kinematic chain*

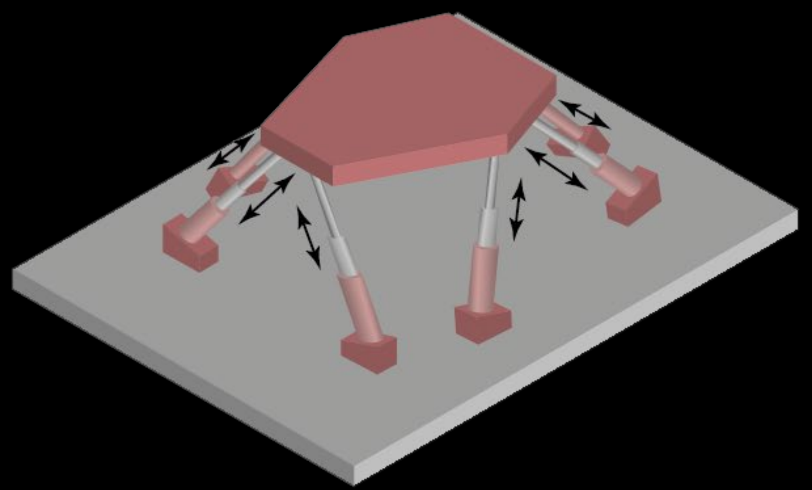





Mobility

- ✓ *Prismatic vs. revolute joints*

Degrees of freedom

- ✓ *3 for position + 3 for orientation*




Workspace

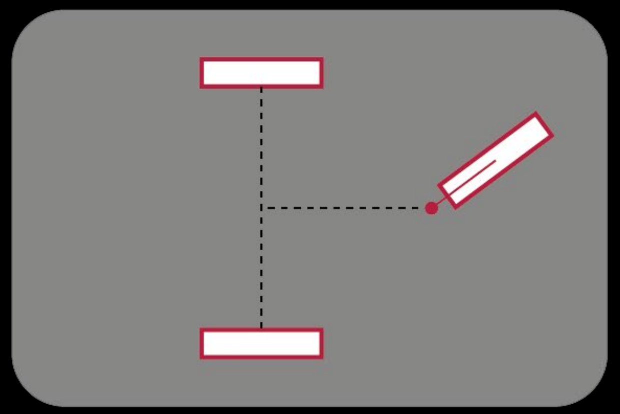
- ✓ *Portion of environment the manipulator's end-effector can access*

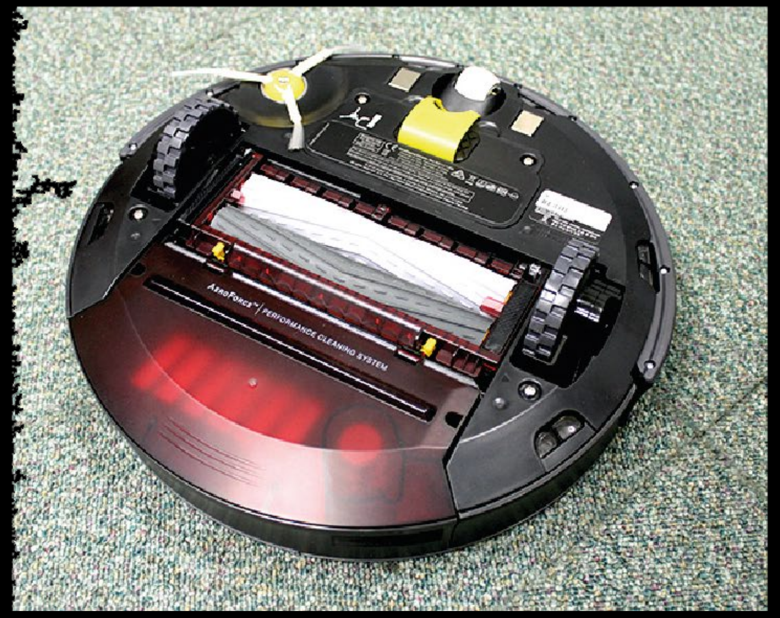
Wheeled Robots

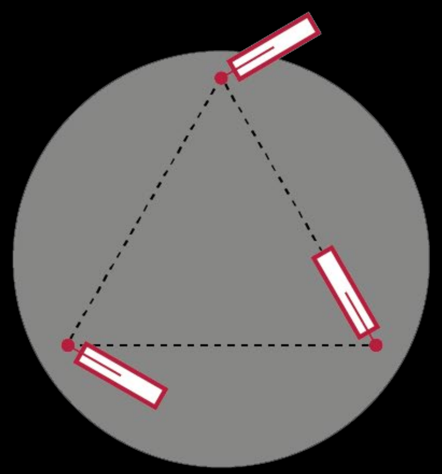
Mechanical structure of mobile robot: set of rigid bodies equipped with locomotion system

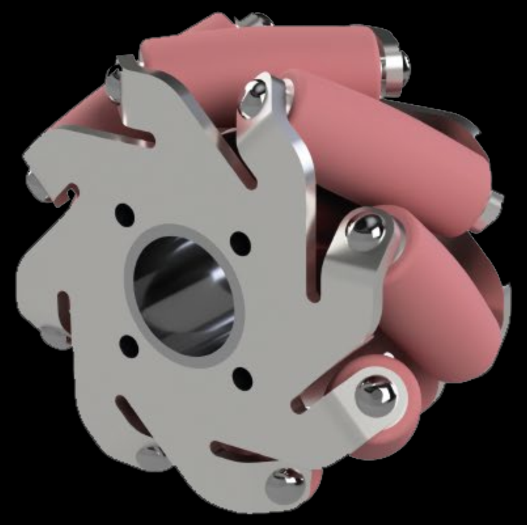
✓ *Mobile robots on wheels*
- *Base (chassis)*
- *Wheels that move it with respect to the ground*
- *Possible trailers (on wheels)*

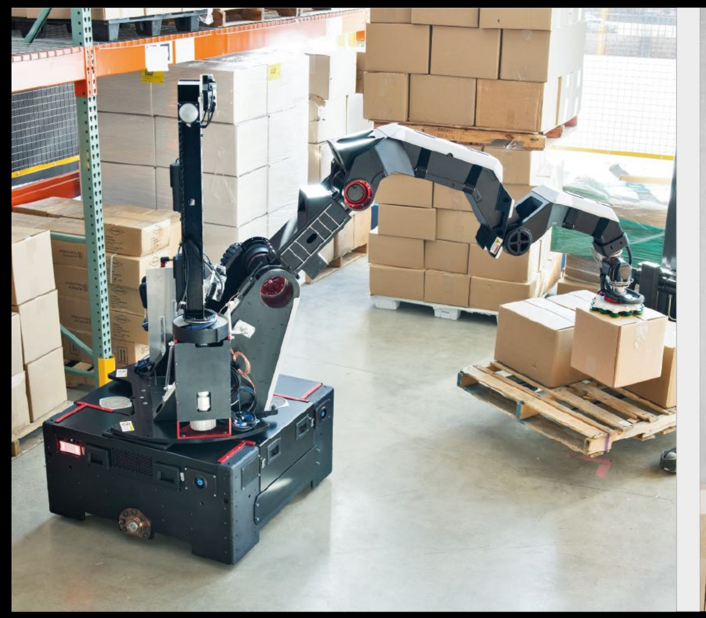
✓ *Mobile robots on legs*
- *Limbs*
- *Foot periodically in contact with the ground (locomotion)*
- *Project inspired by living organisms (biomimetic robotics)*

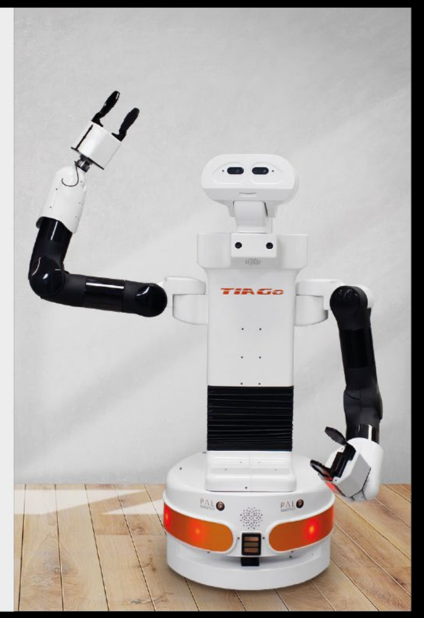




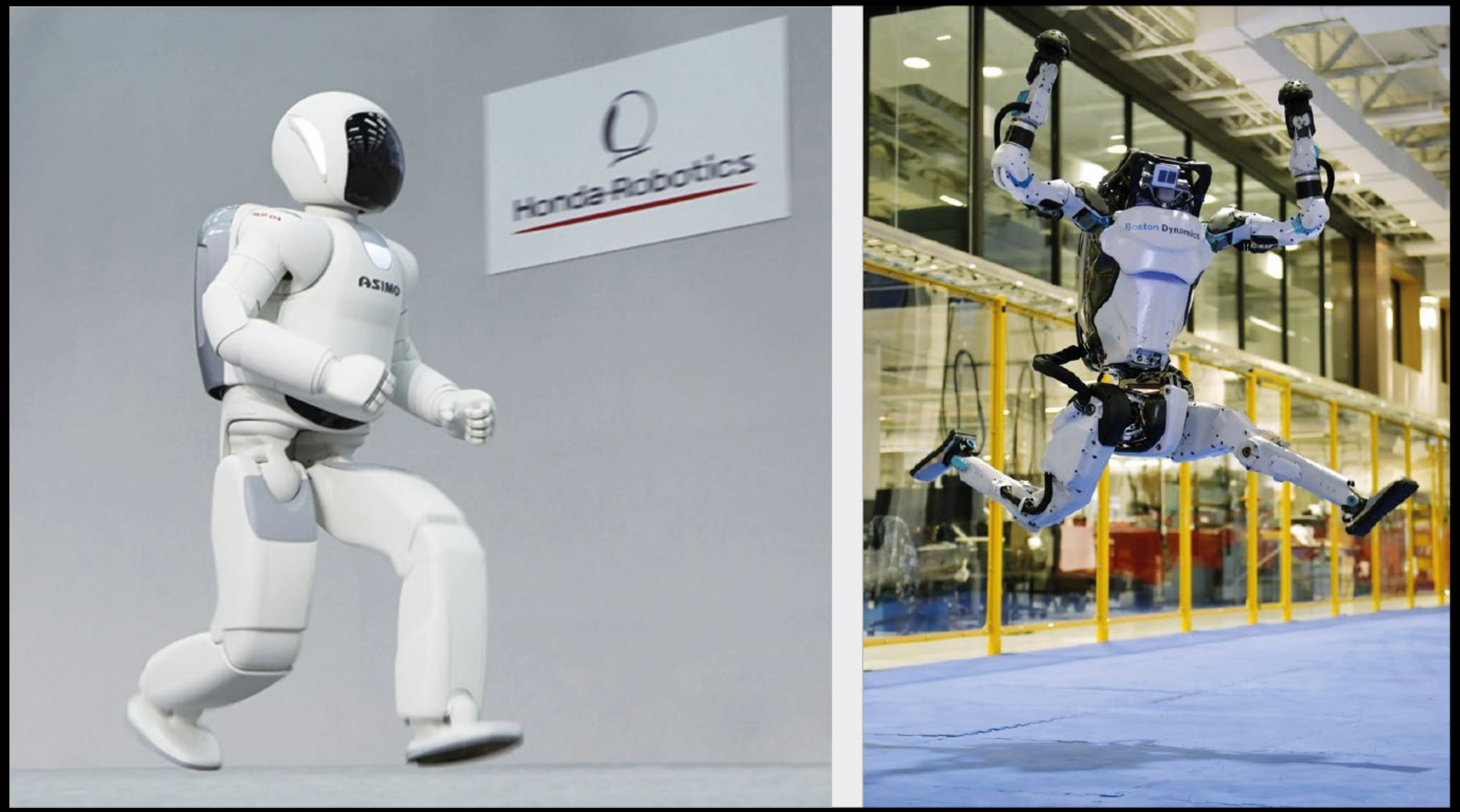








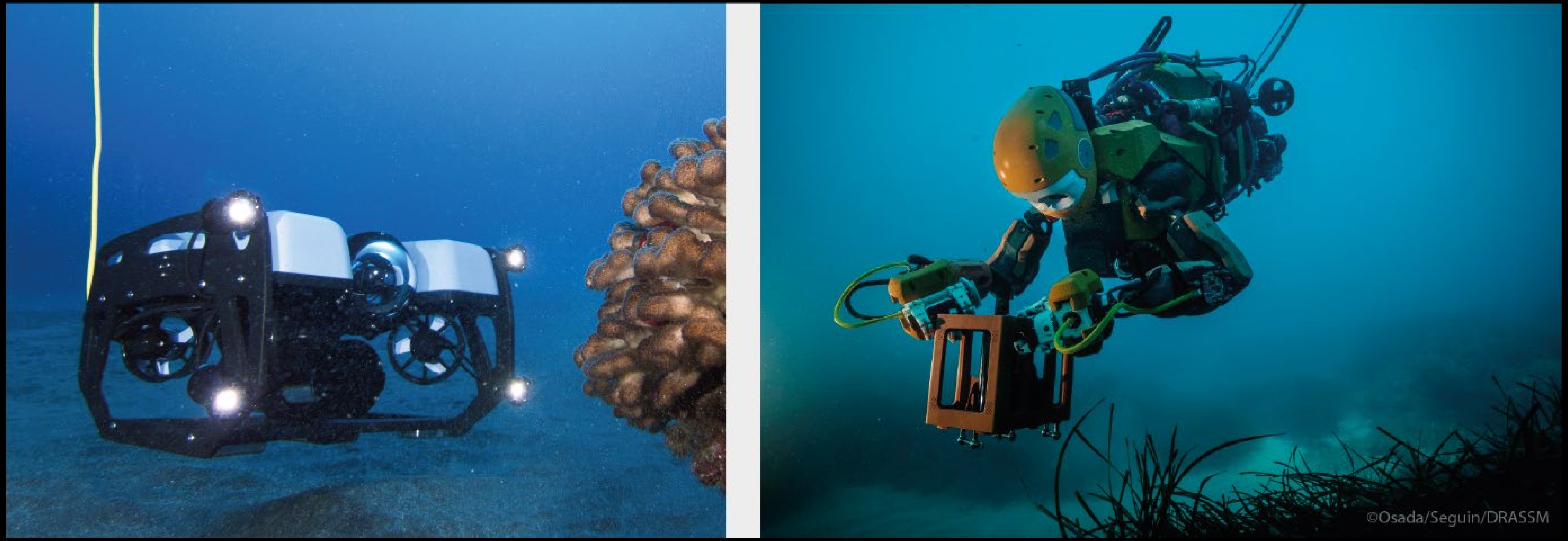
Other Robot Structures



Bipeds

Flying

Walking



Underwater

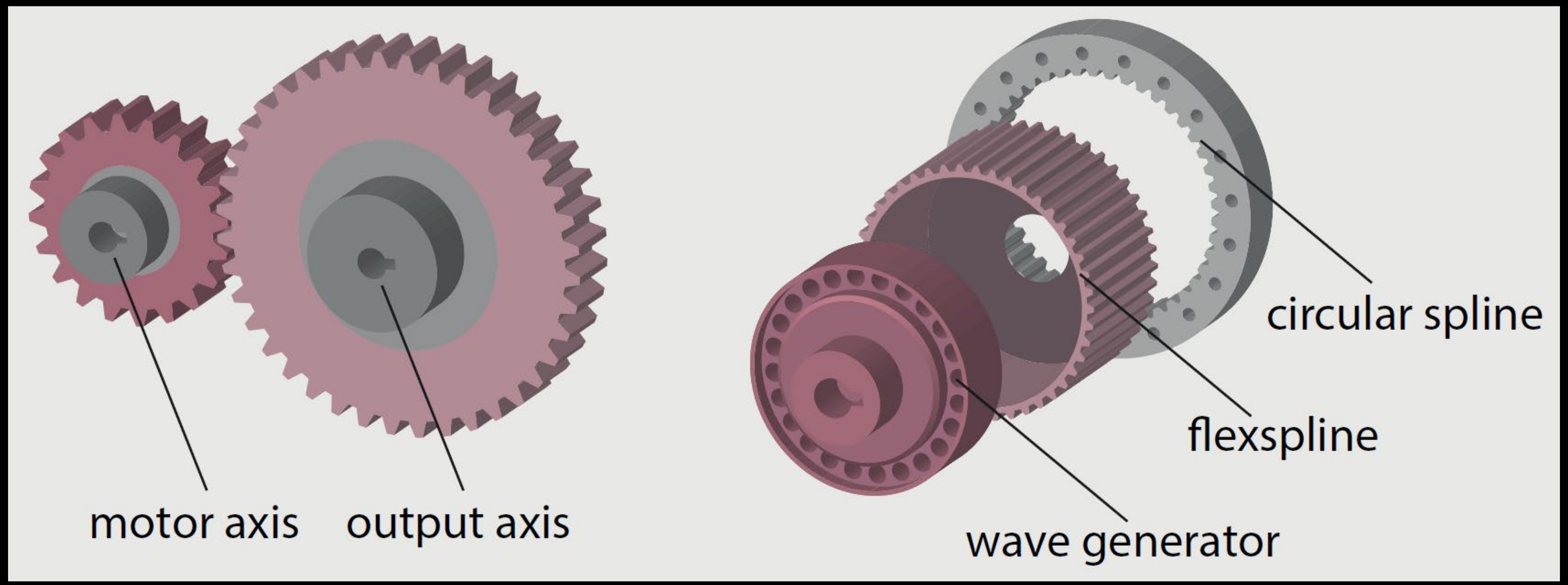
Actuation

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

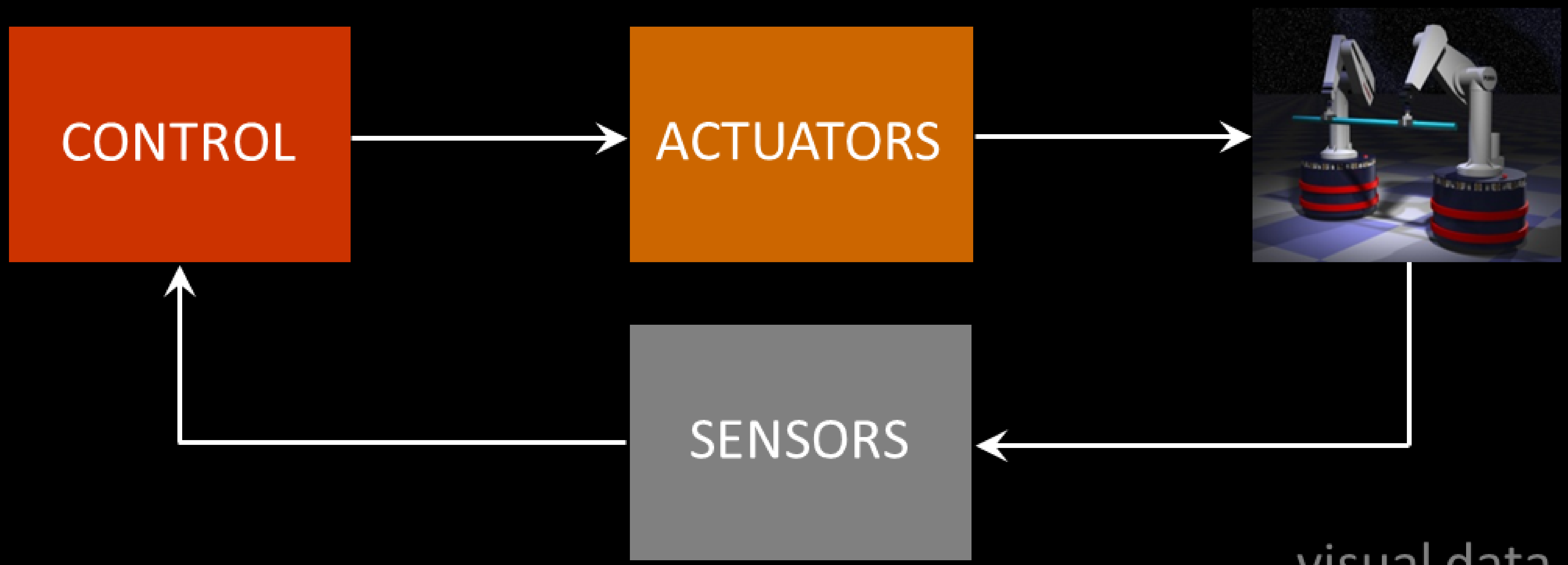
- ✓ *Joint position, velocity, and torque (in manipulators as well as other robots with revolute joints, e.g., legged robots)*
- ✓ *Angular position or velocity of wheels (in wheeled robots)*
- ✓ *Position, orientation, velocity and acceleration of a body of the robot (in mobile robots)*

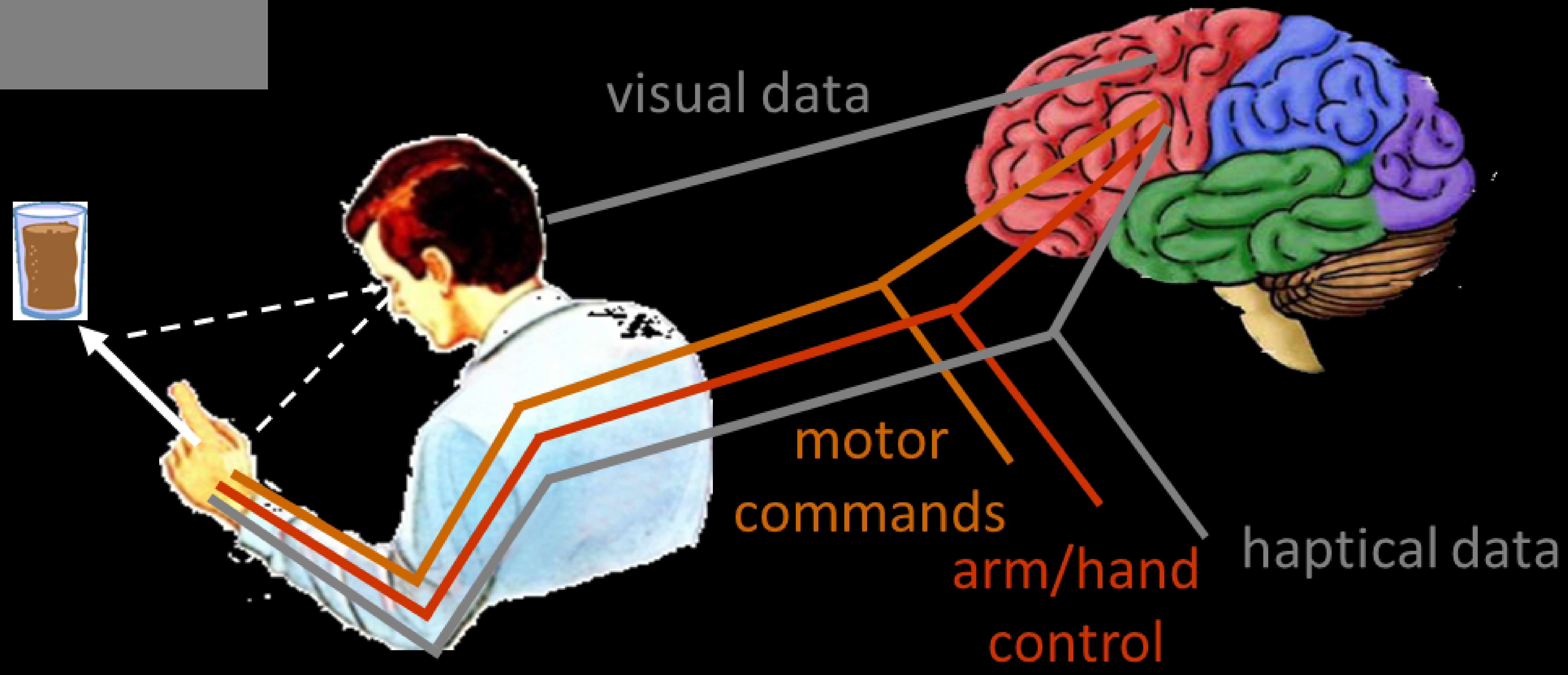
Exteroceptive sensors

- ✓ *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*

Robotics

intelligent connection of perception to action





Artificial Intelligence

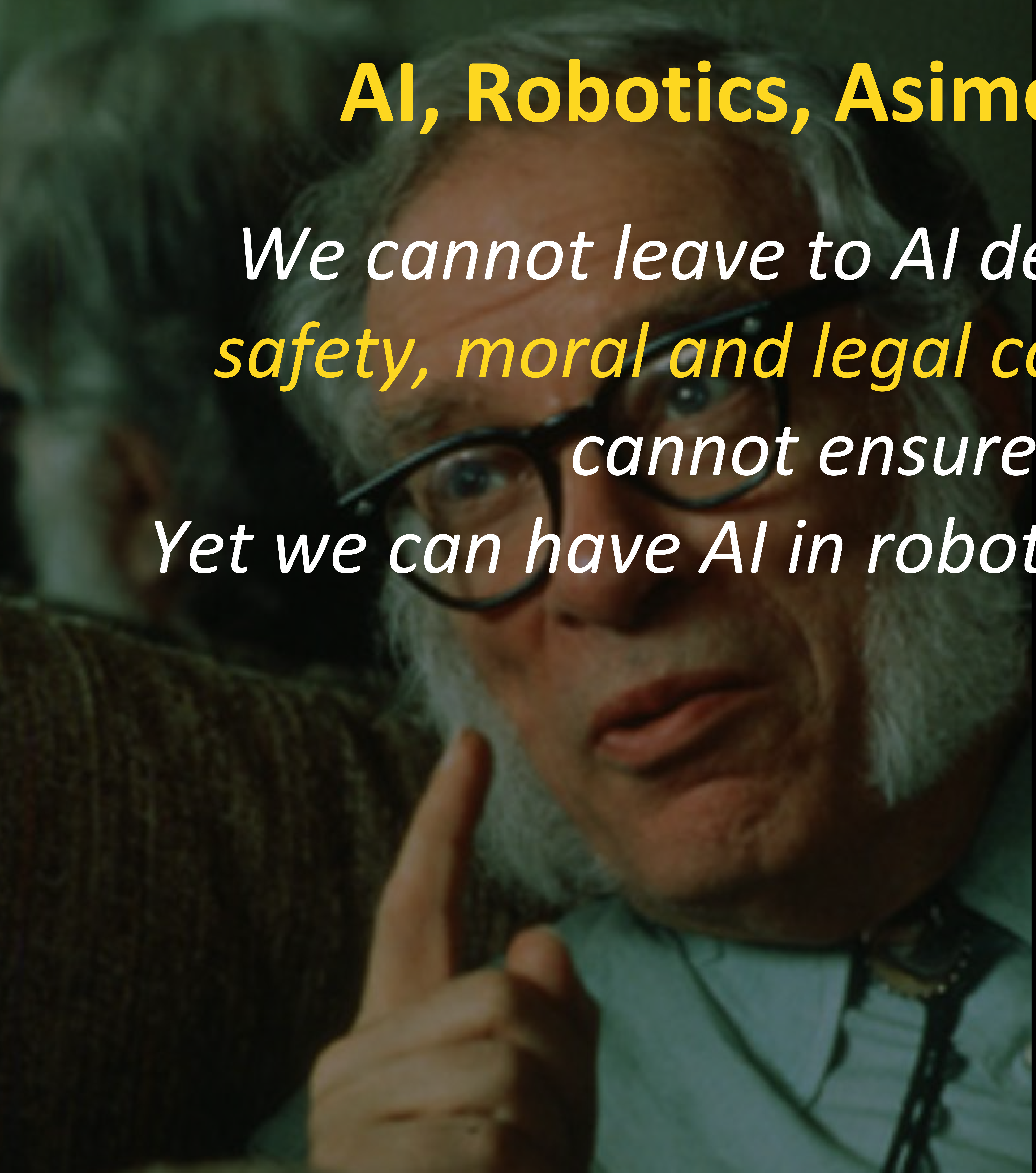
Computers mimicking functions and logics of ***human mind***

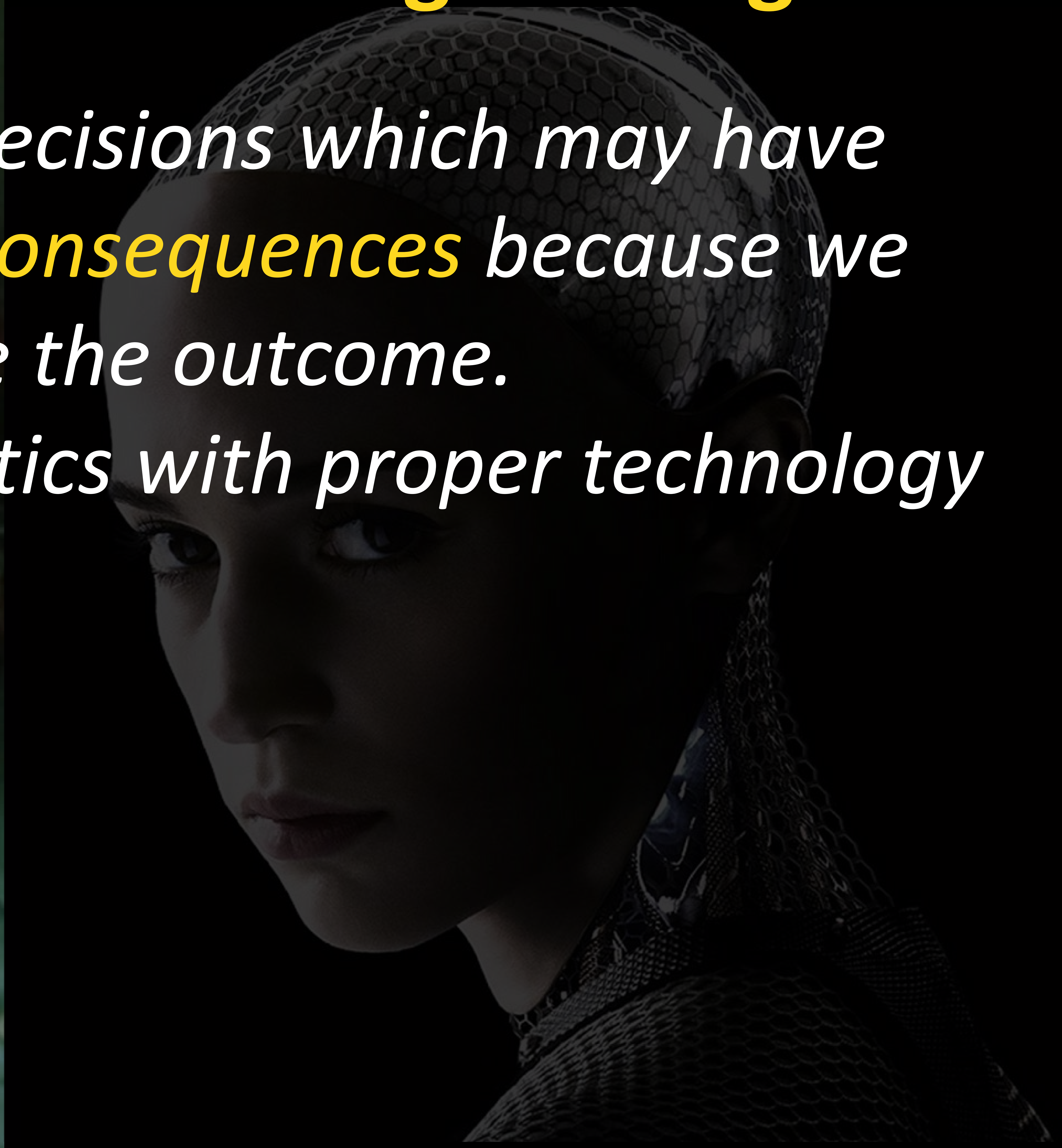
Cortical homunculus

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



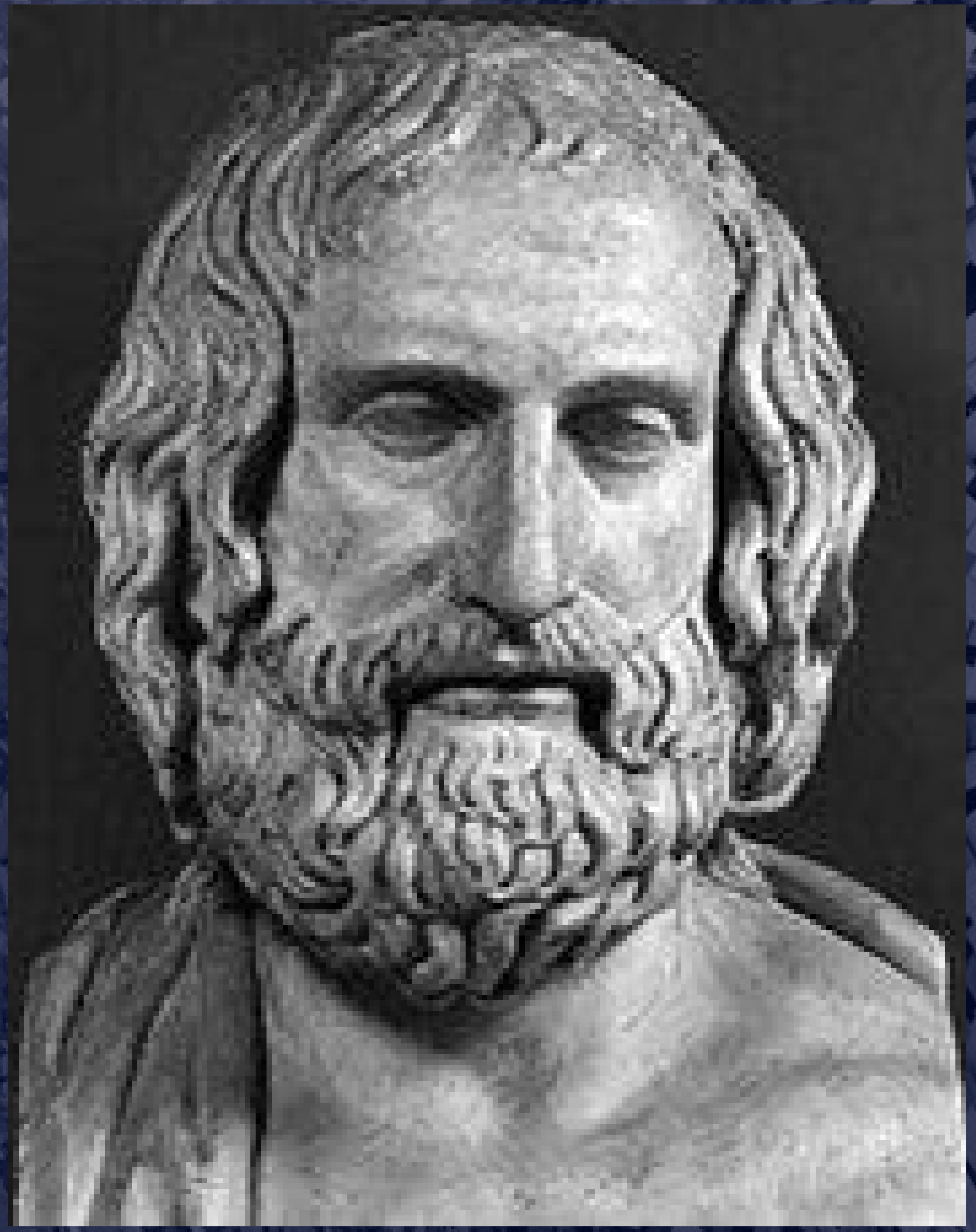


The Big Challenge

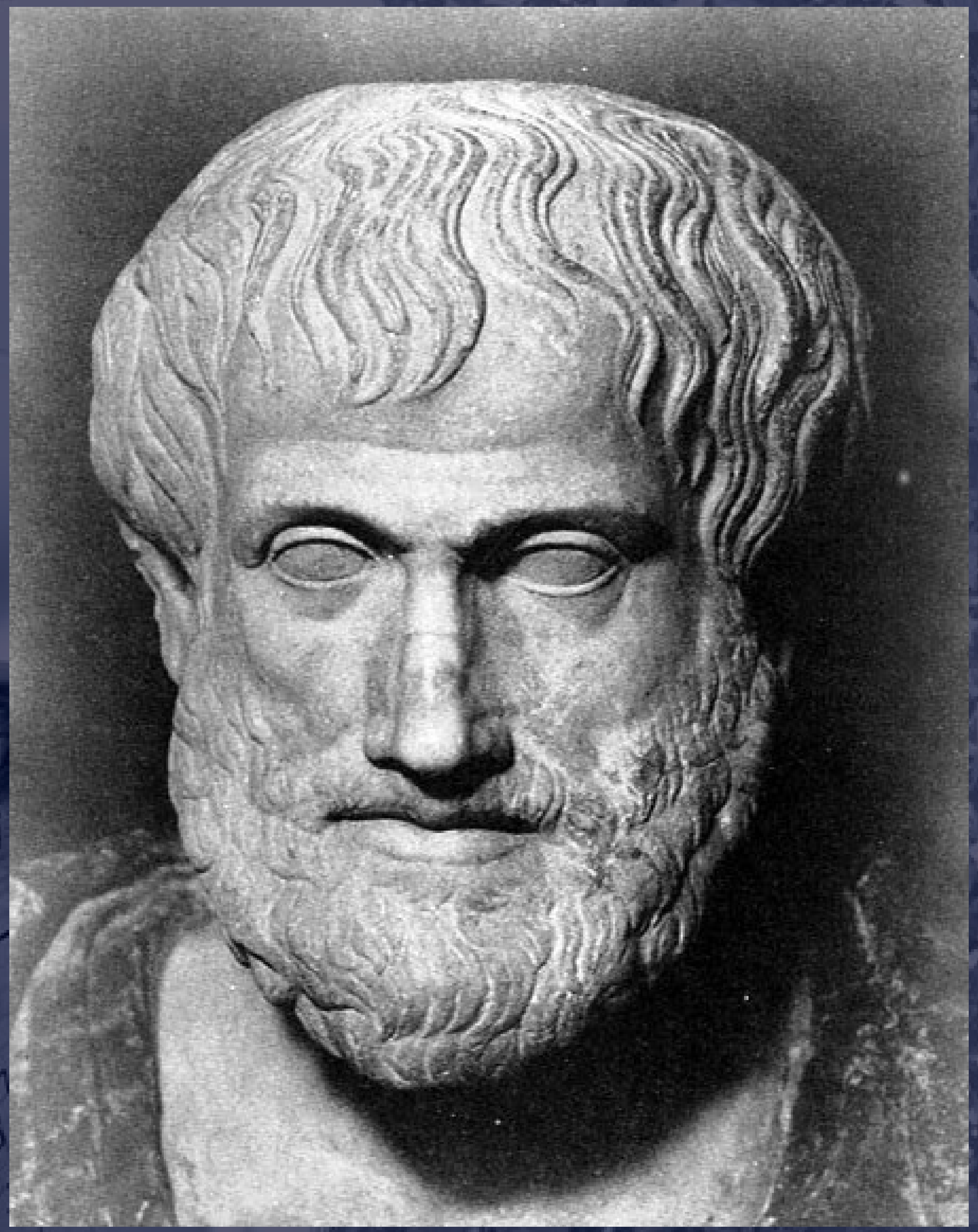
Manipulation

Cognition

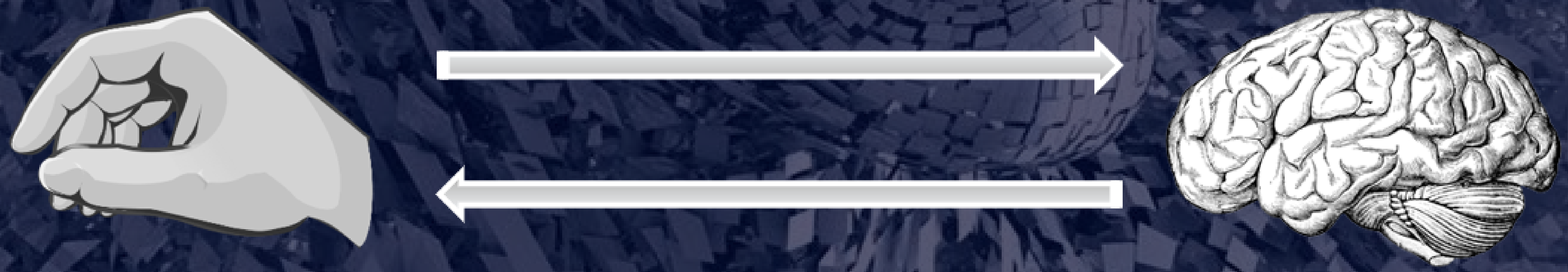
Body vs Mind



Anaxagoras



Aristotle



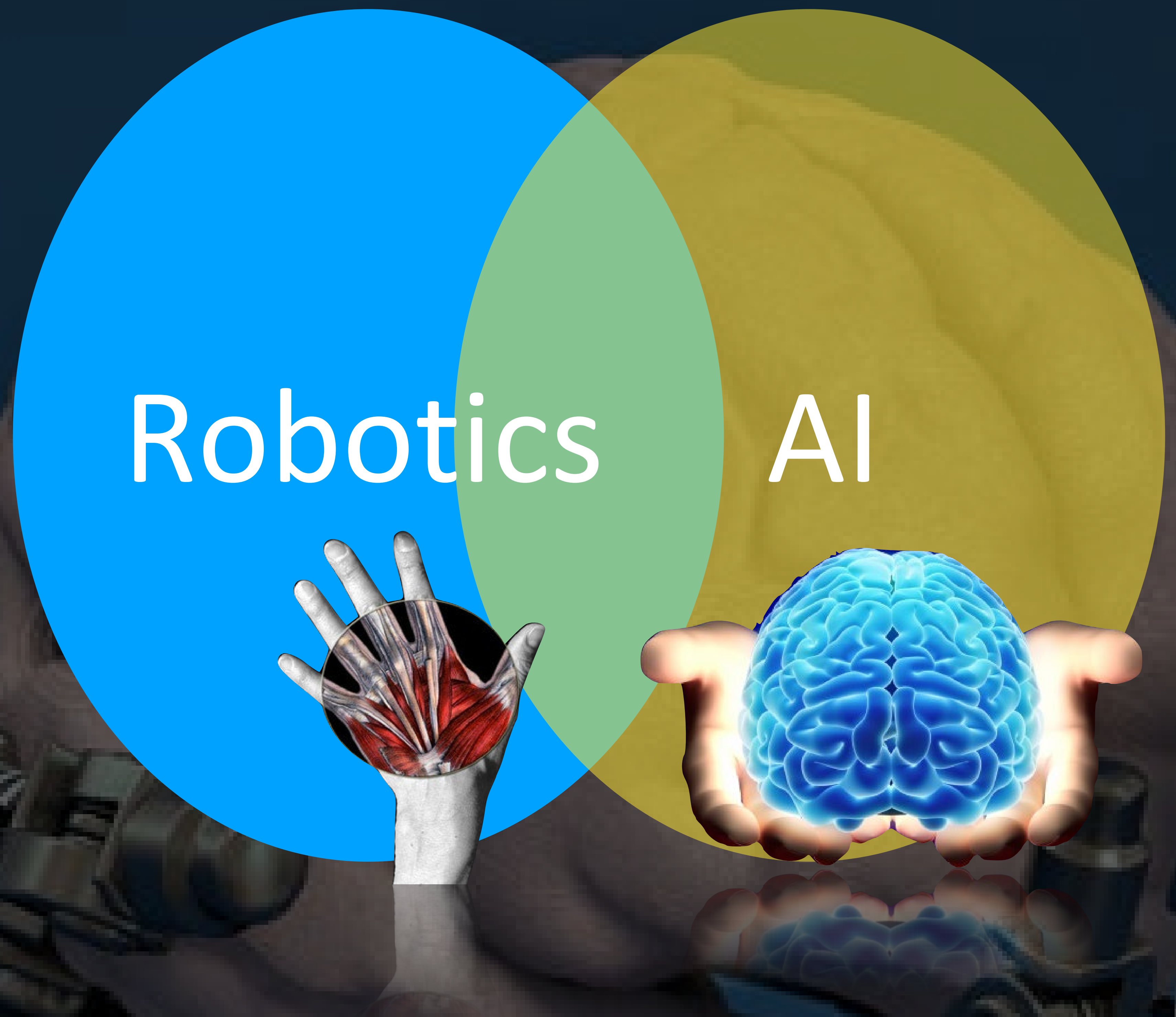
Embodiment

Physical Artificial Intelligence

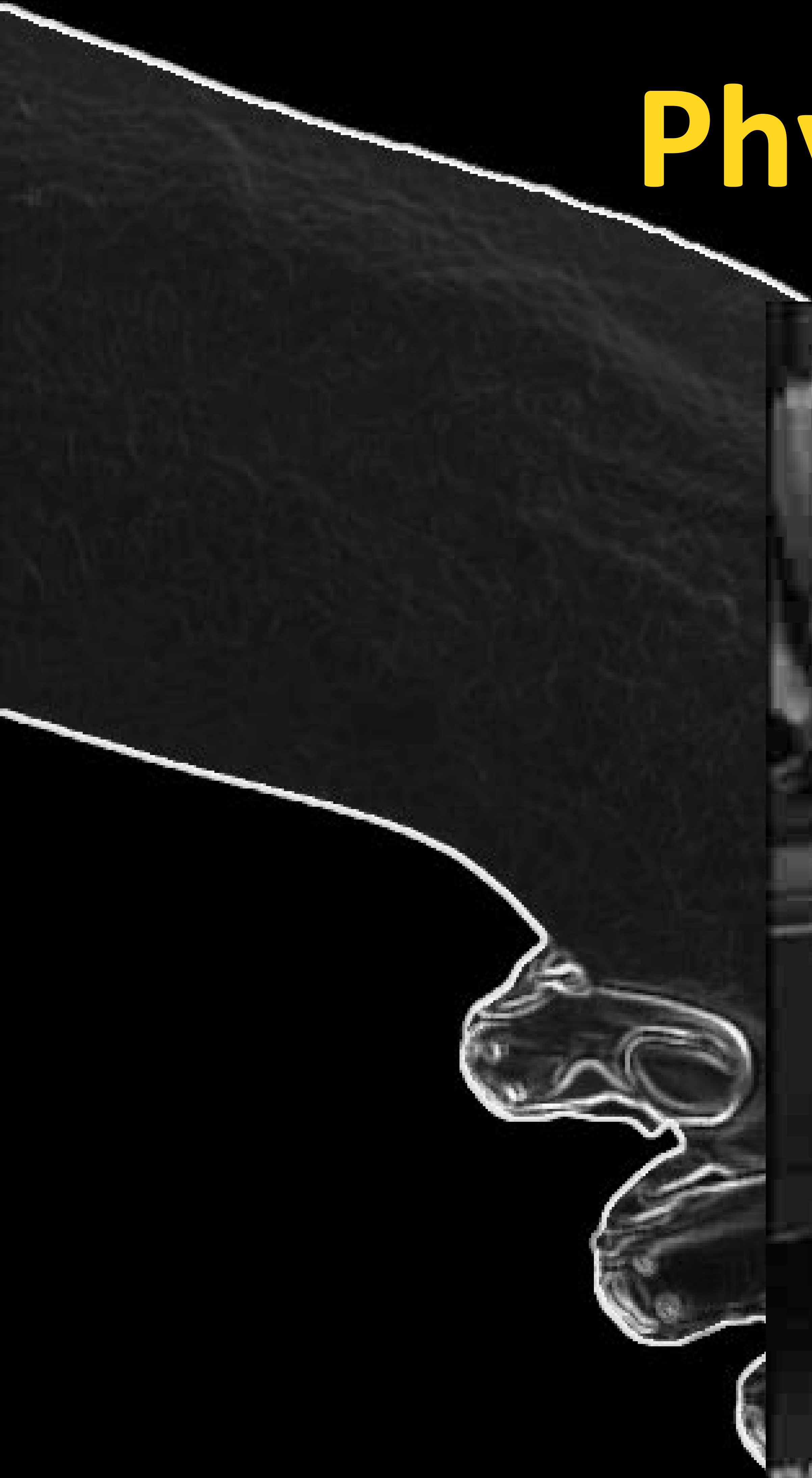
The big challenge is found at the intersection of Robotics and AI

Physical Artificial Intelligence is MUCH harder (Moravec)

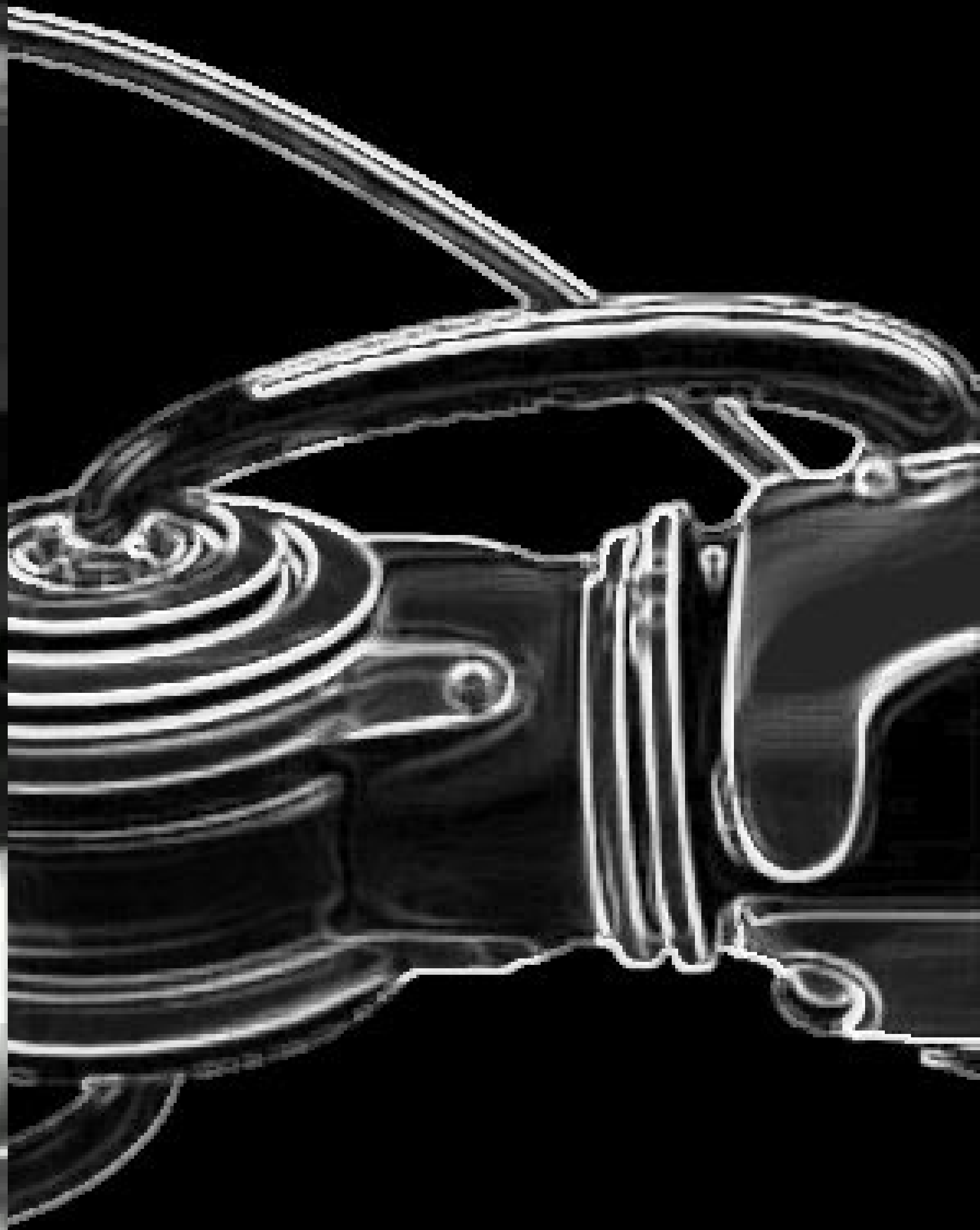
AI is not deterministic and "blind" use in robotics can be potentially dangerous



Physical Human–Robot Interaction



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



Nature Italy, Antonio Bicchi & Bruno Siciliano (2021)

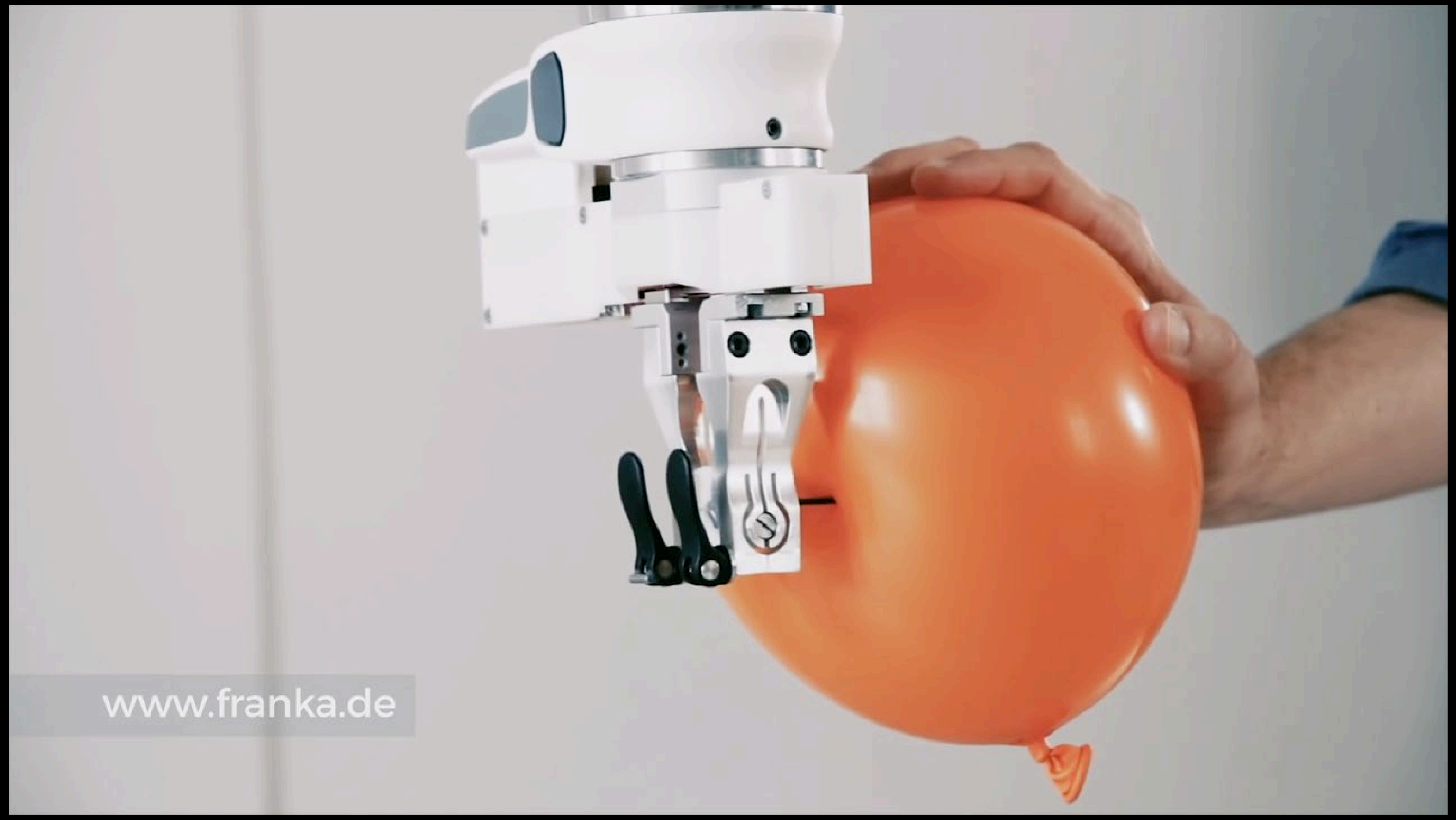
Industry 4.0

n–Robot
eration
bot)

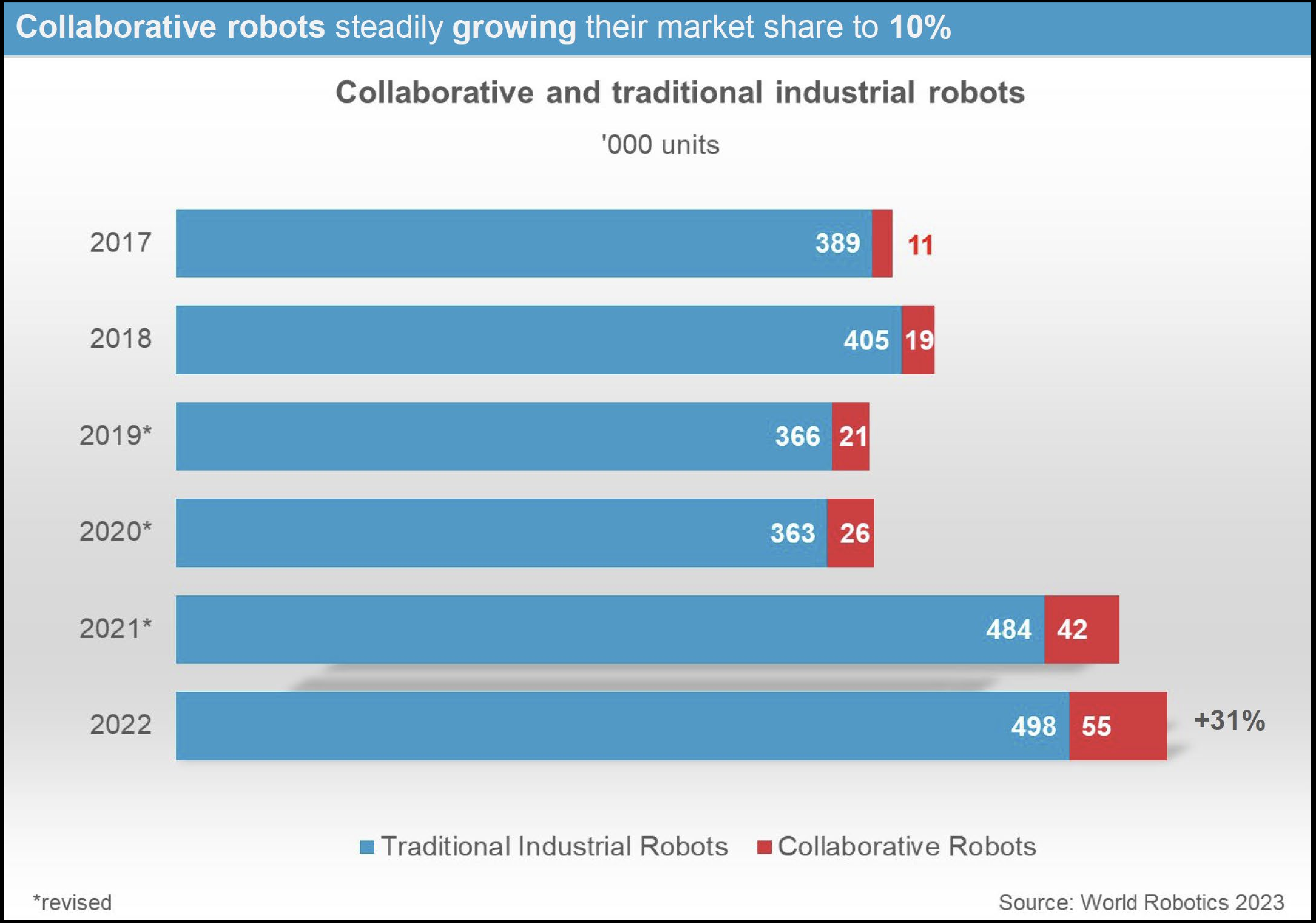
Cobot

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)*

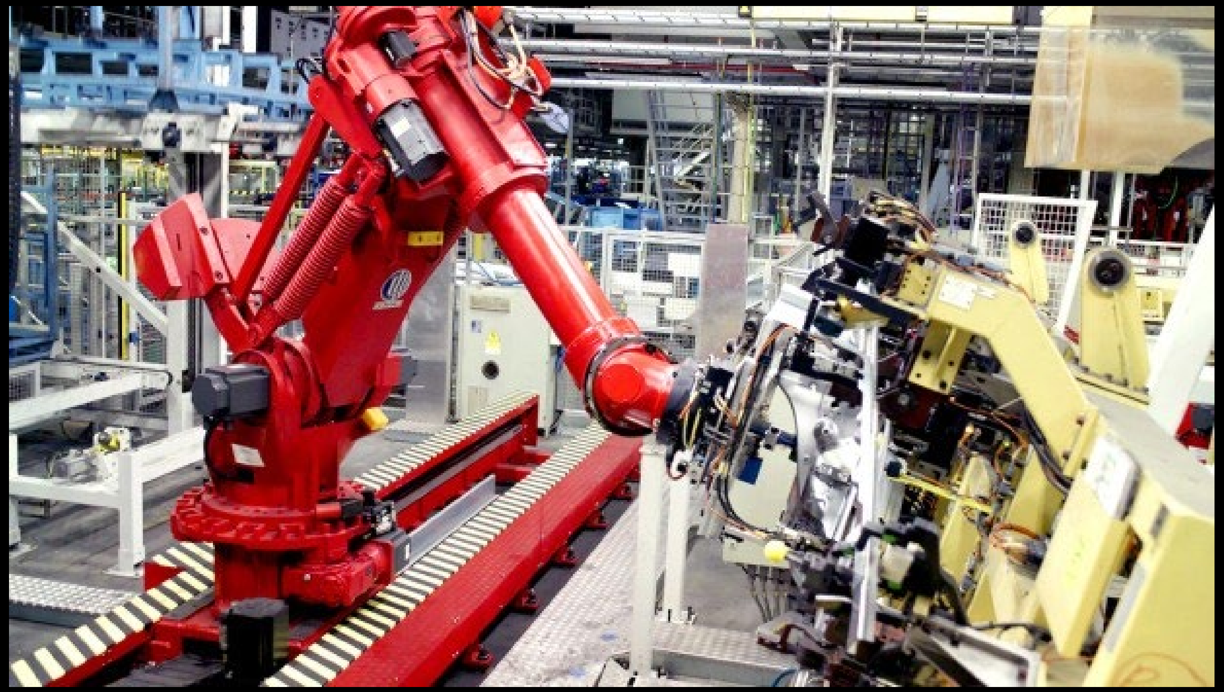


Collaborative vs Traditional Industrial Robots

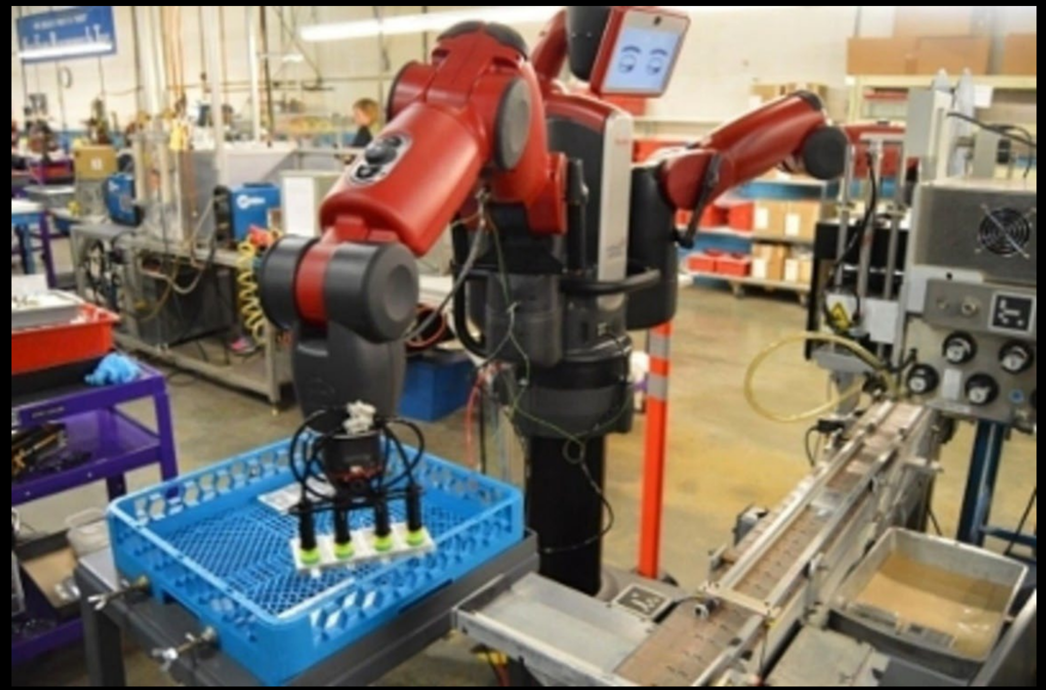


From Factories to Our Homes

LEVEL OF AUTONOMY

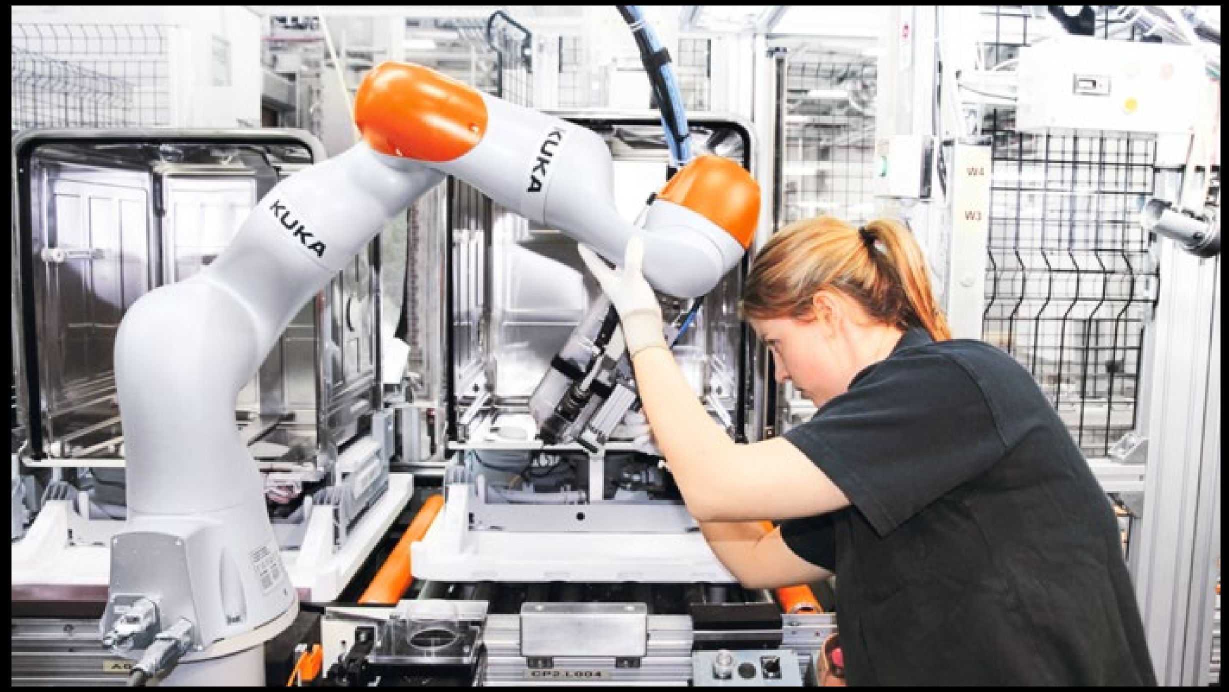


Automatic machines executing programmed tasks with high levels of accuracy, speed and repeatability in a perfectly known environment



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

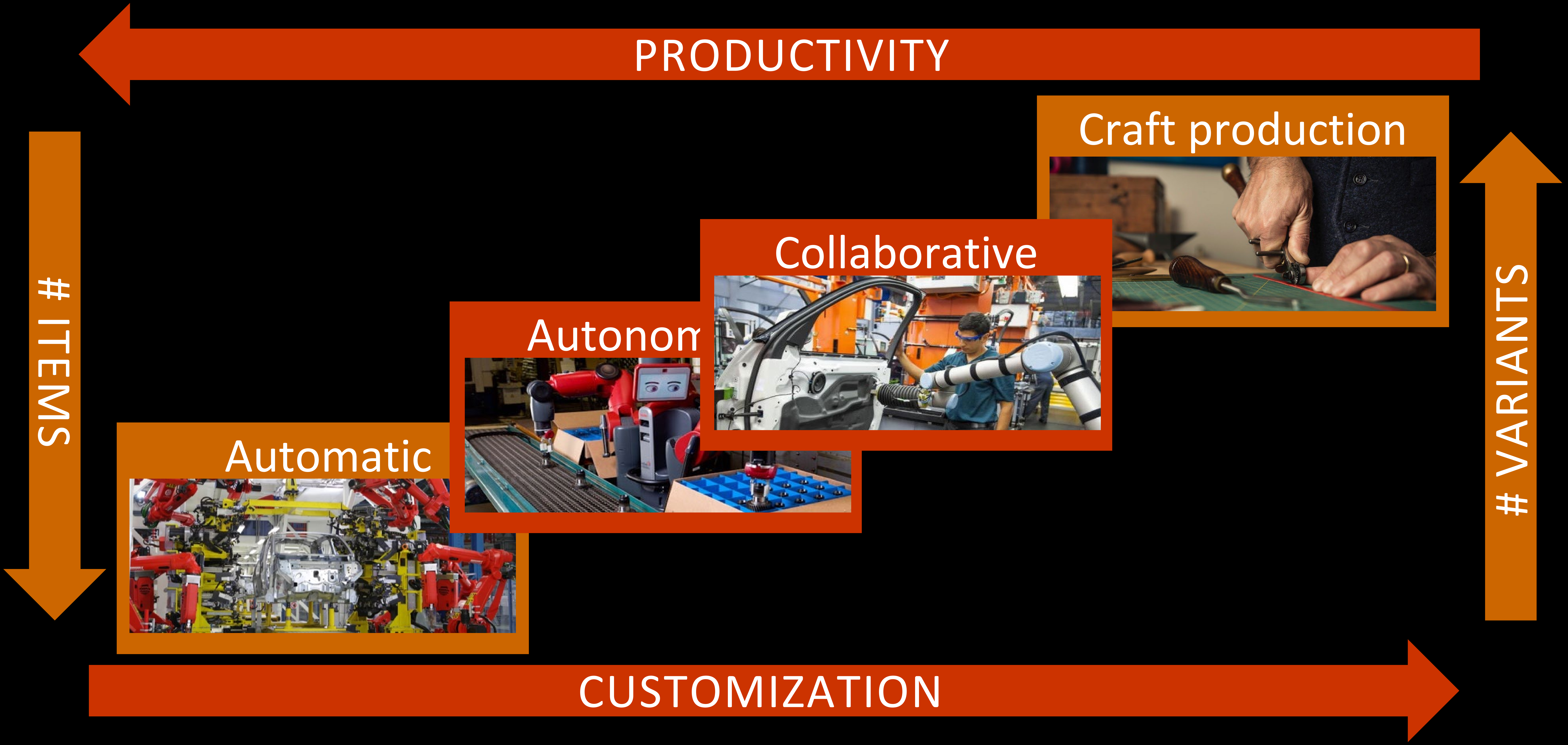
Machines confined in fenced areas, designed to handle the dull, dirty and dangerous tasks in place of human workers



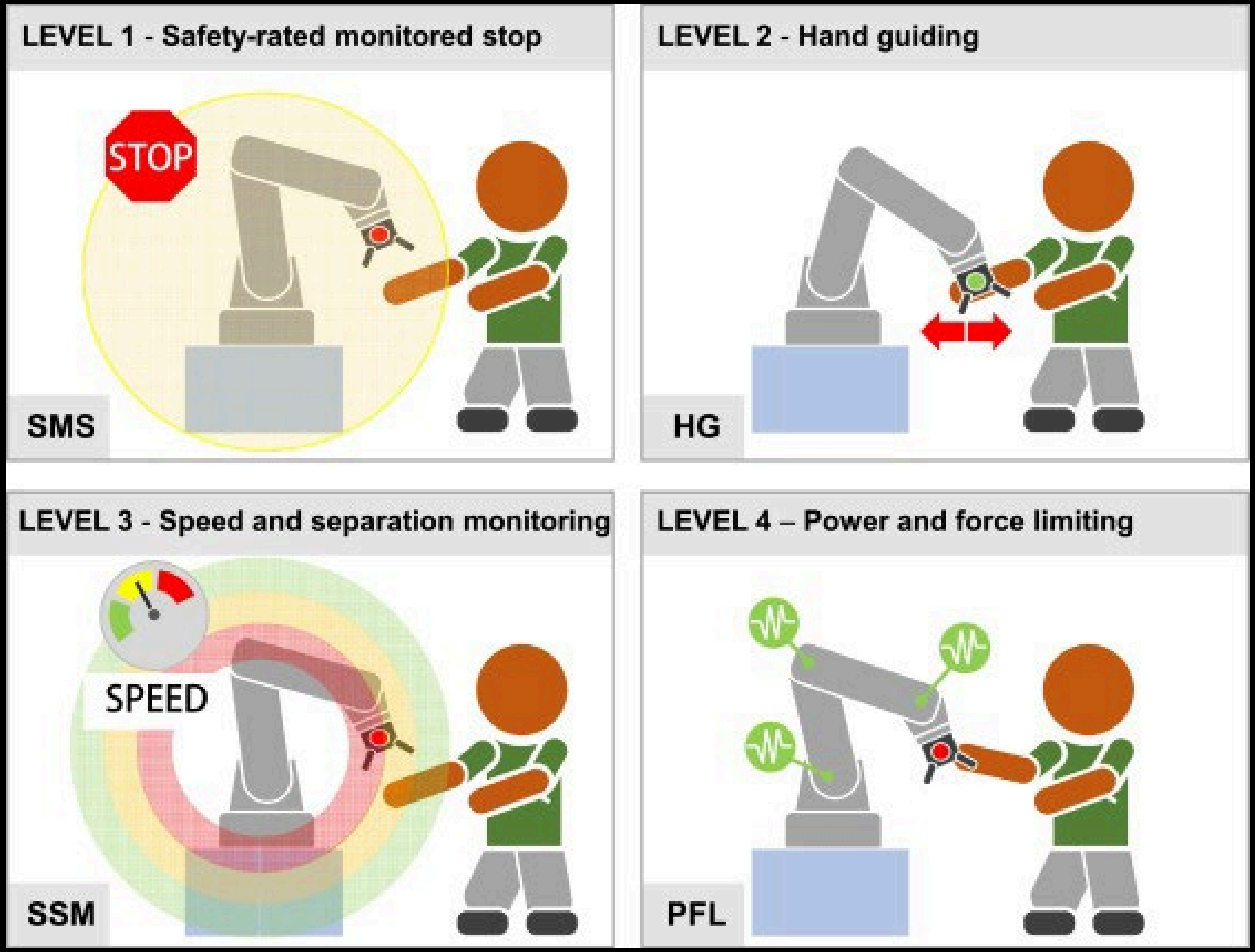
Lightweight machines able to work safely in the same workspace or even physically collaborate with humans

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

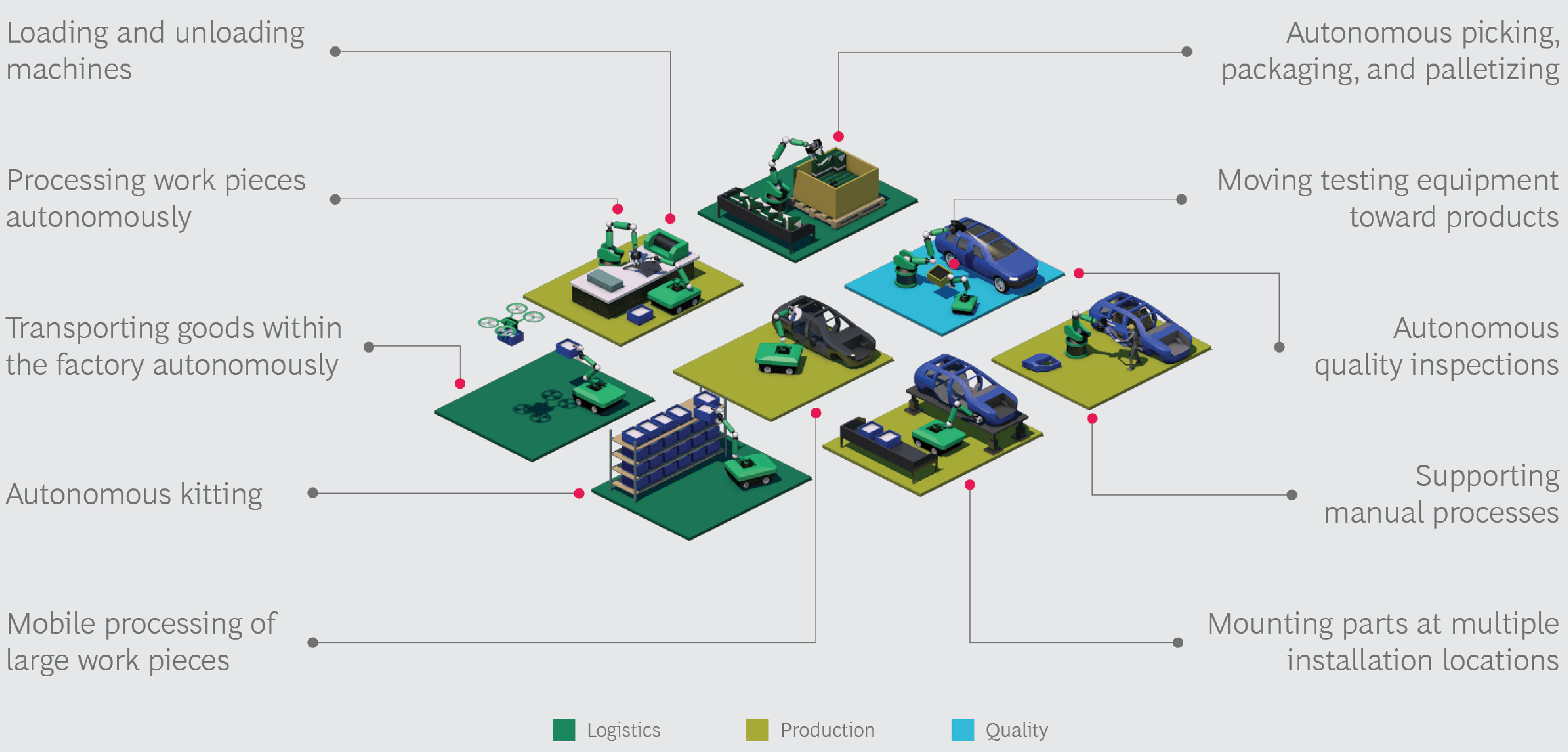

legs support


tool holding

https://exoskeletonreport.com

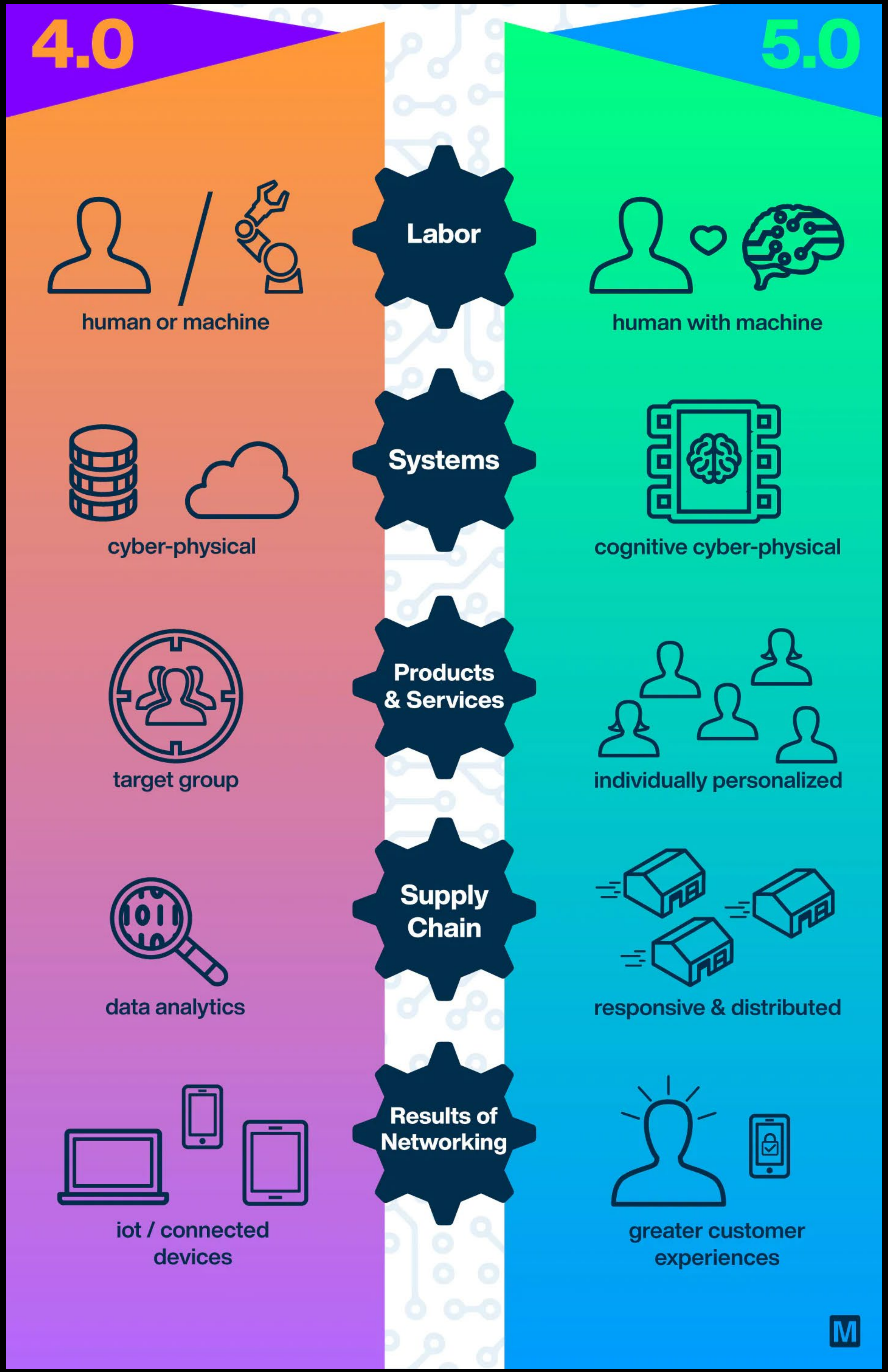
The Factory of the Future

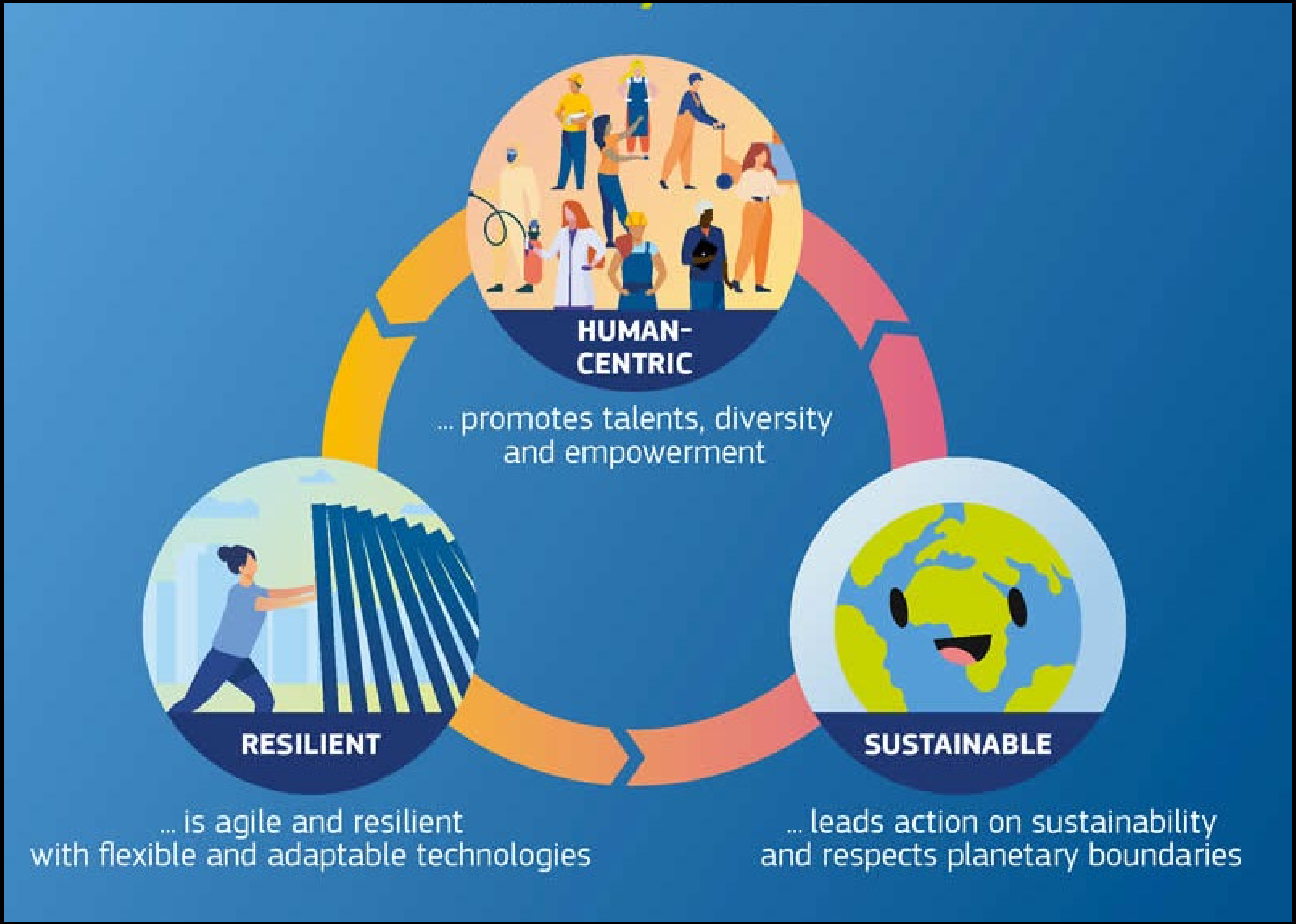
Exhibit 3 | Advanced Robotics Has Many Applications in the Factory of the Future



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

Towards Industry 5.0





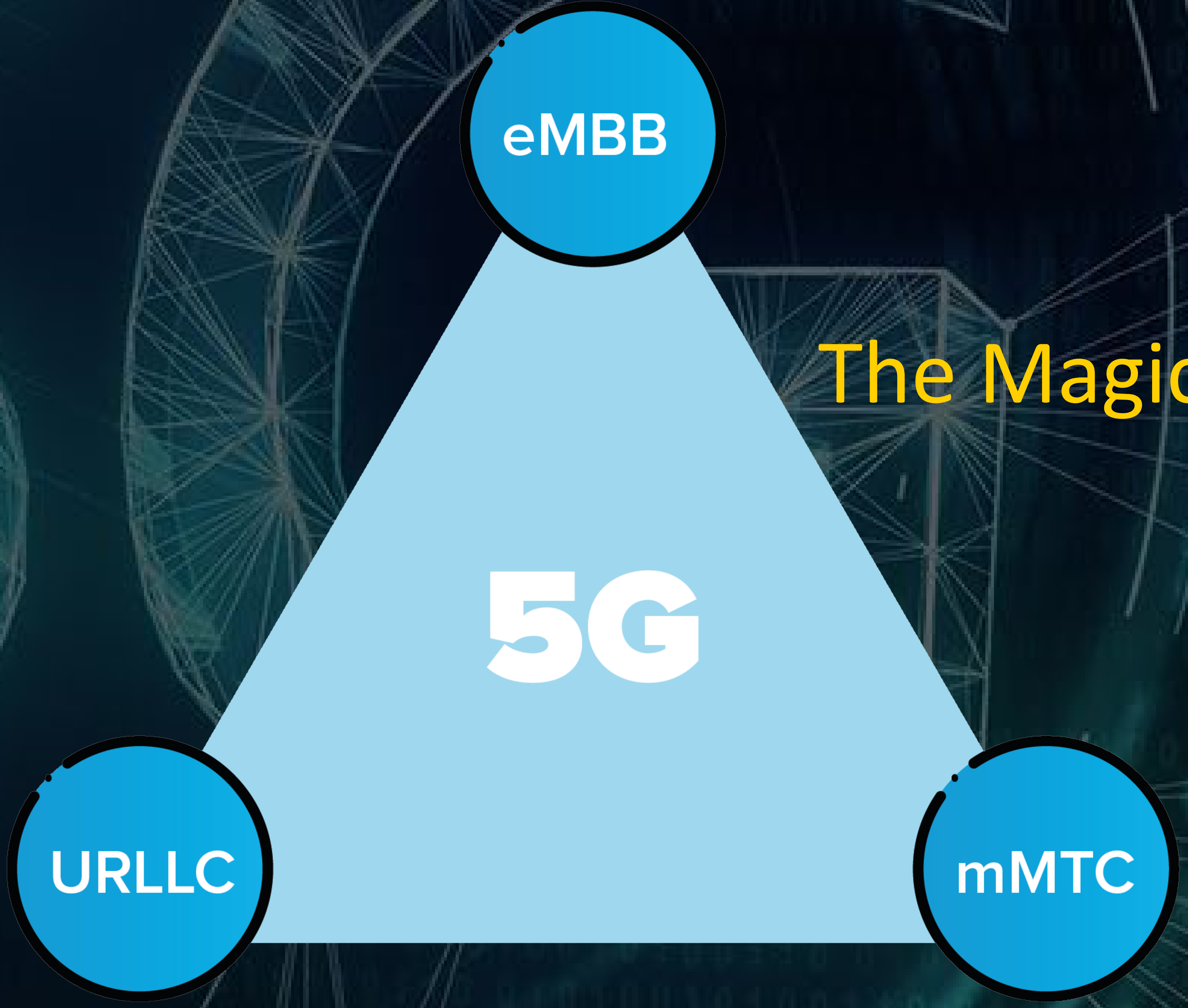
Fifth Generation of Wireless Technology

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

Extreme Mobile Broadband



The Magic Triangle

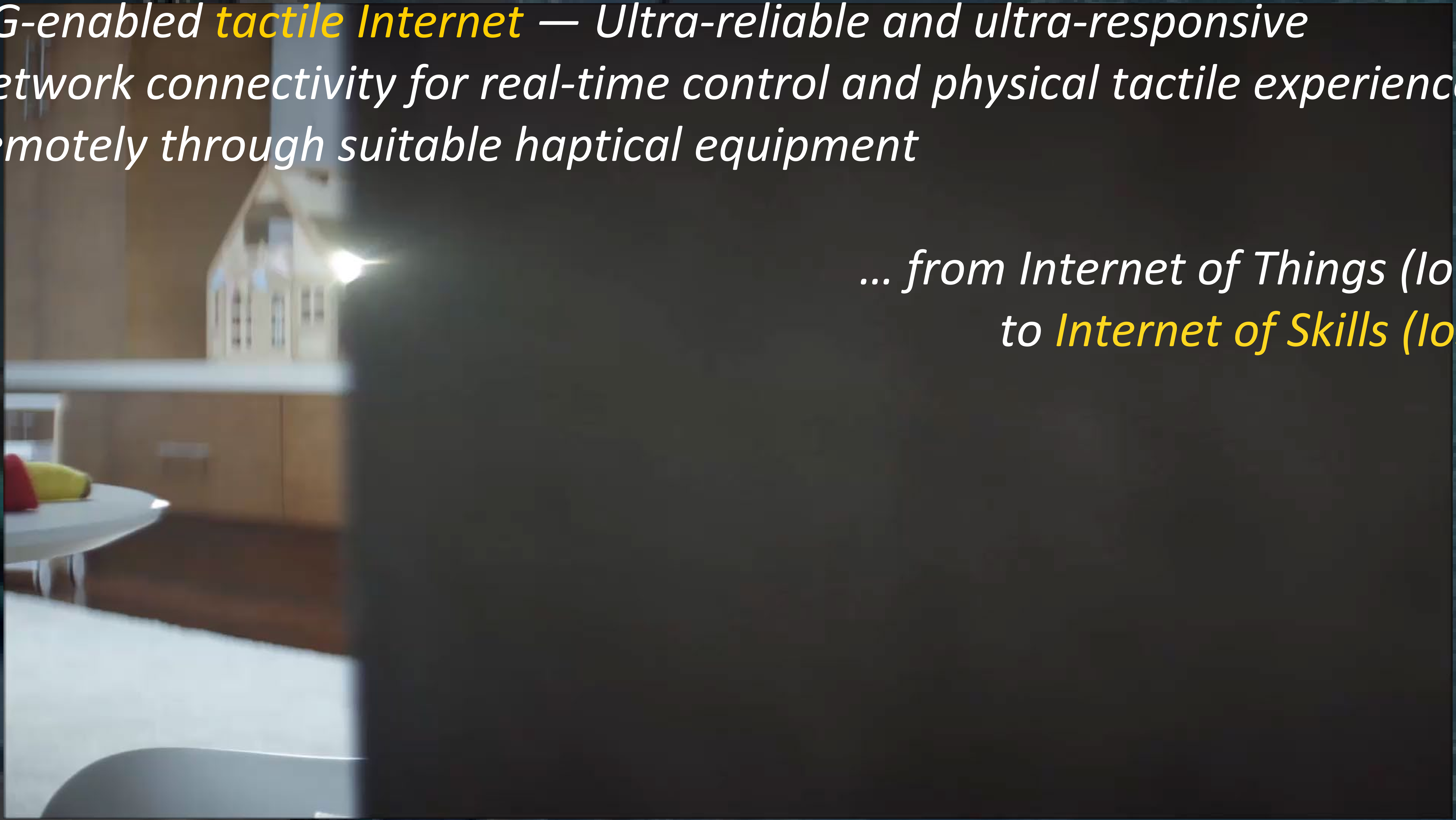
Ultra-Reliable Low-Latency Communication

Massive Machine-Type Communication

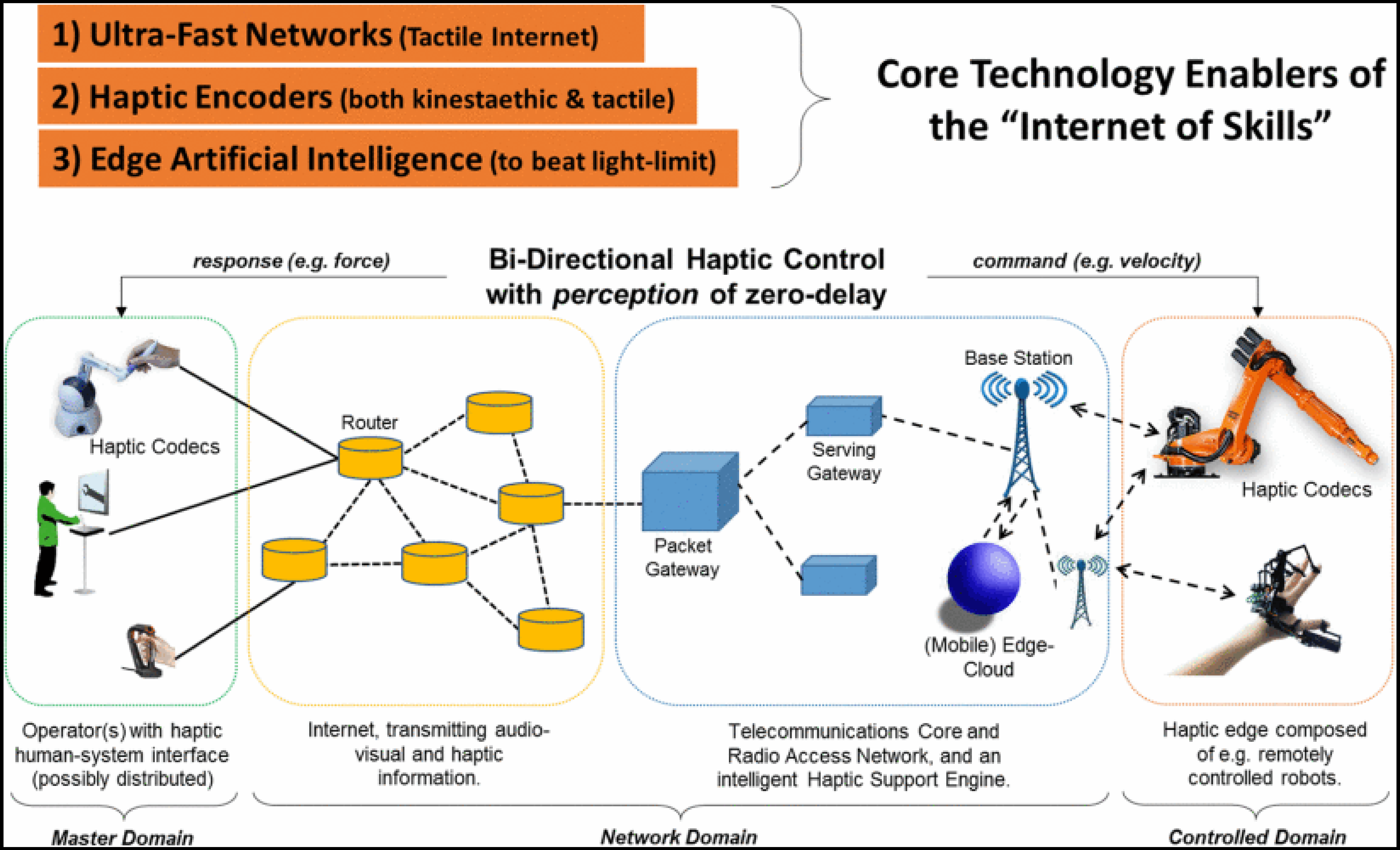
The Invention Age

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



Pillars of Next Generation Robotics

The Factory, Reimagined

NDT, Autonomous

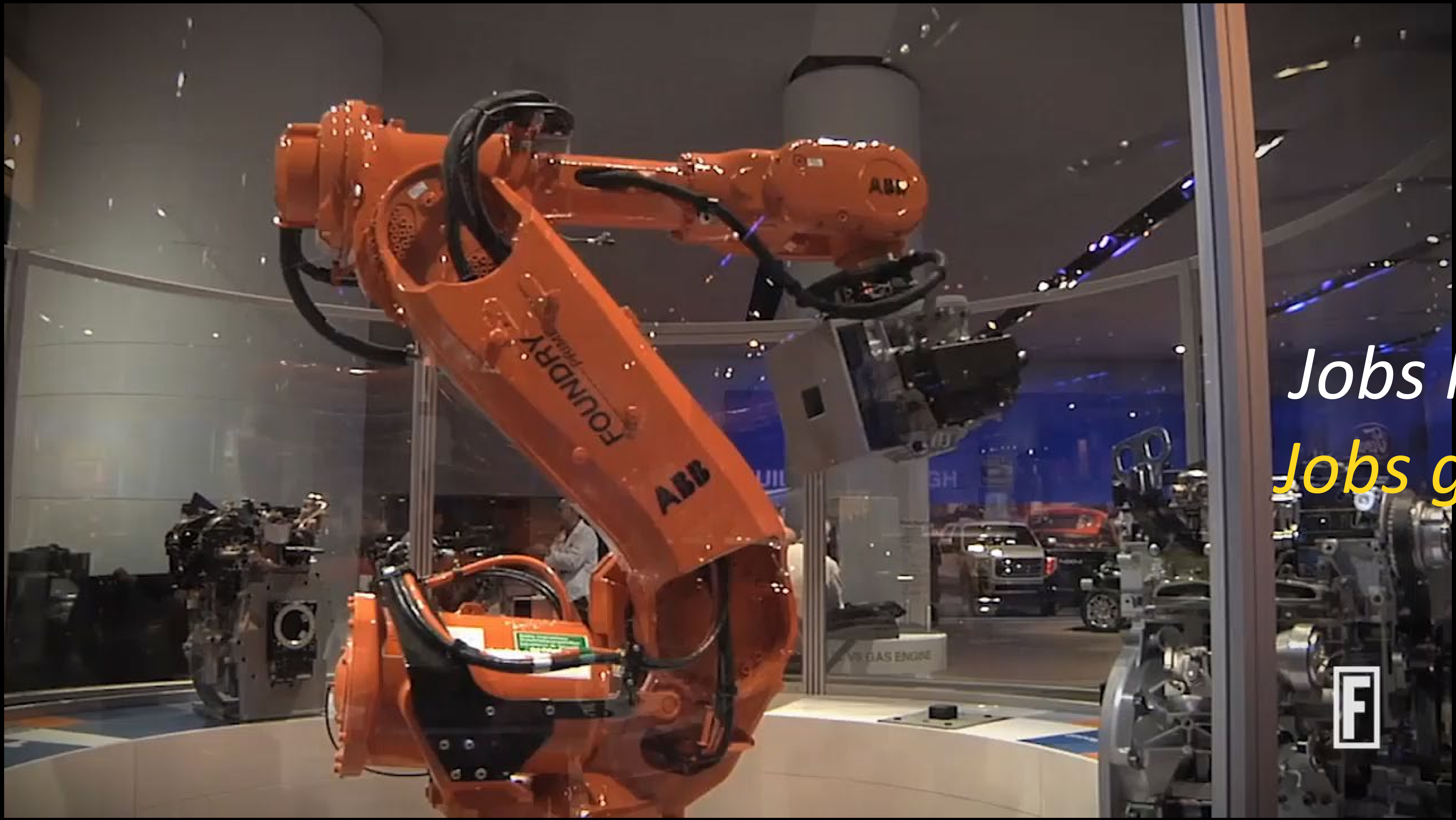
The AI Data Robotics Association

euROBIN

Healthcare, Revolutionized

Robots on the Field, Unthetered

Robots as Job Killers?

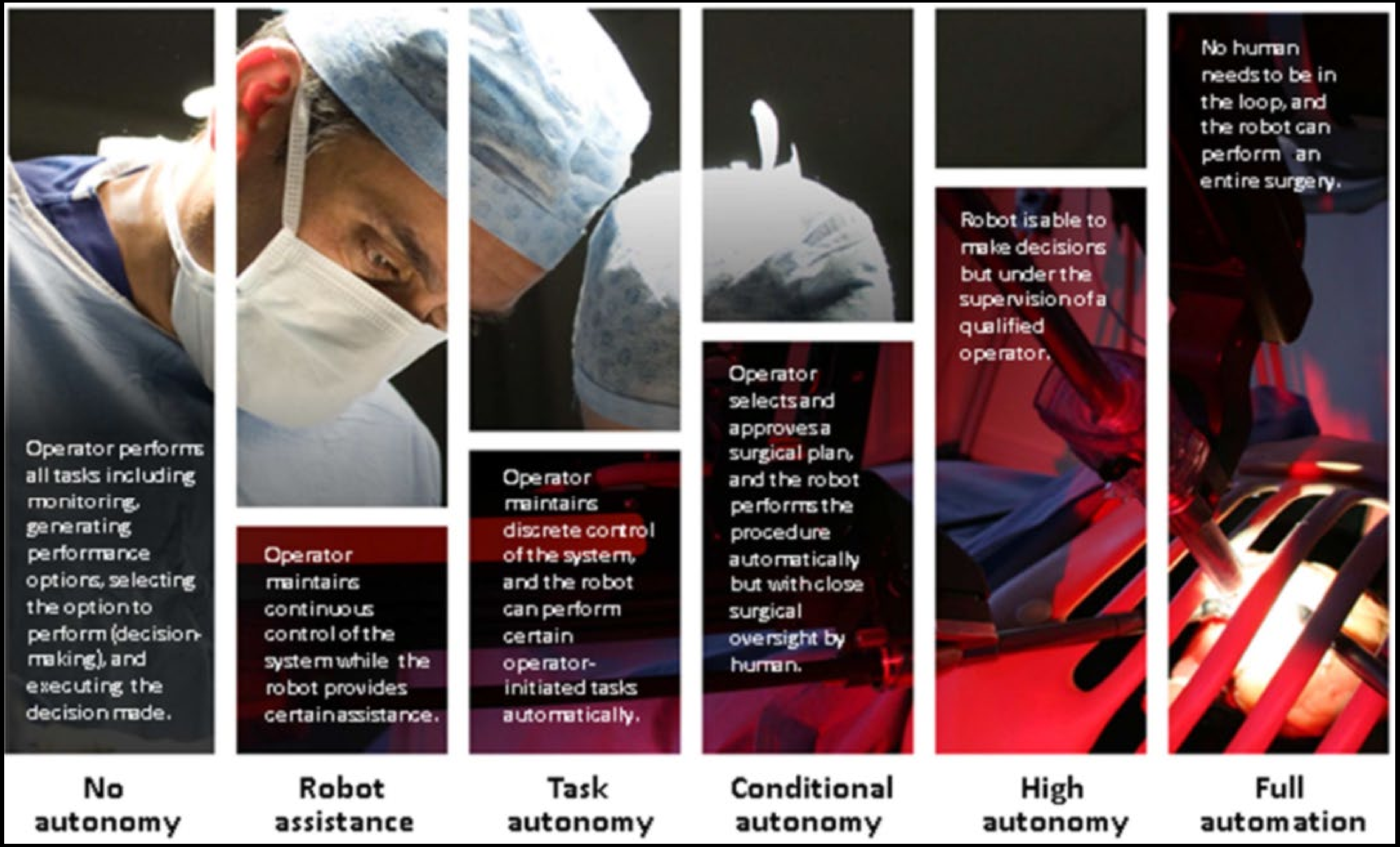


Jobs lost …

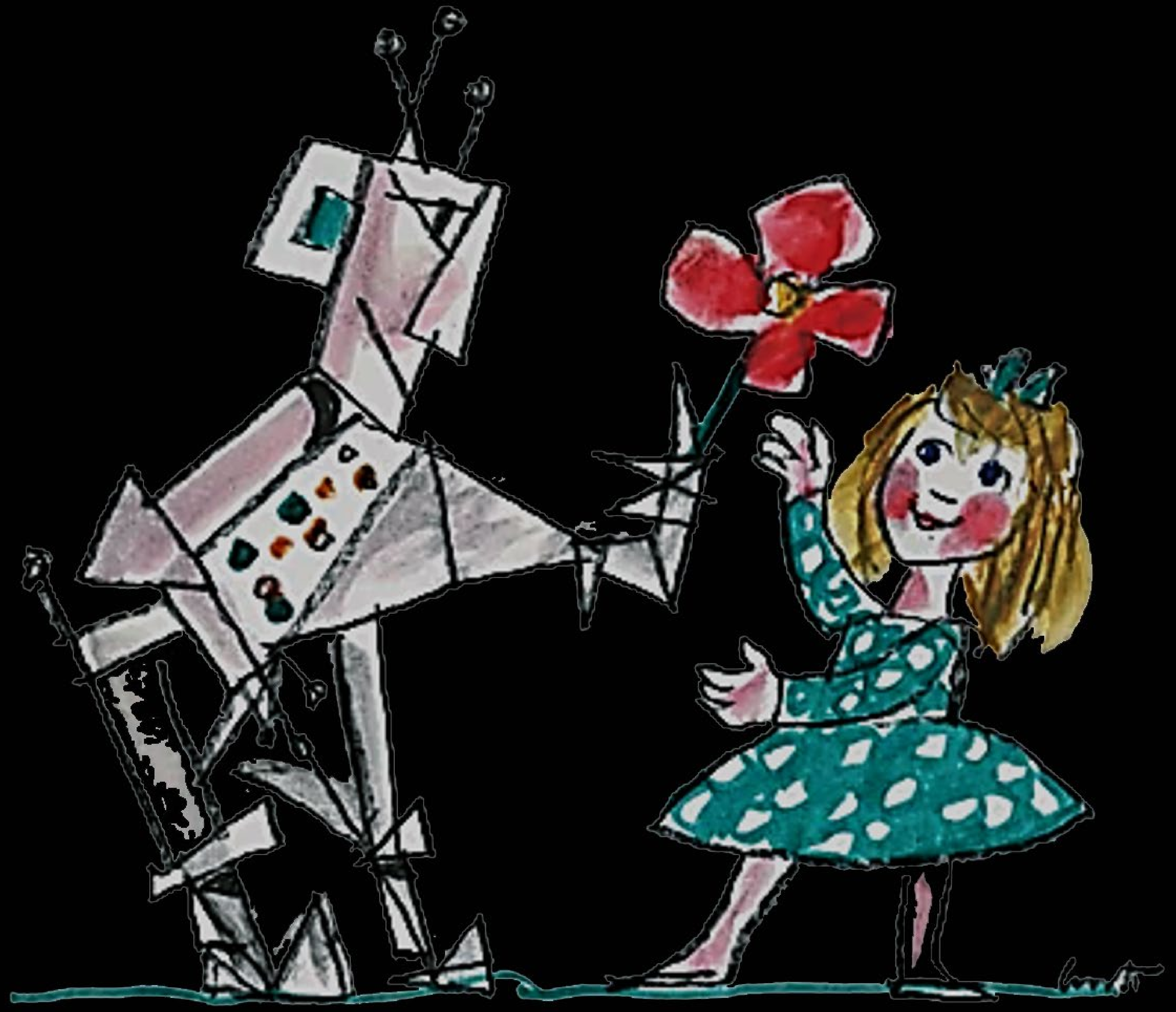
Jobs gained

Levels of Autonomy

L0 L1 L2 L3 L4 L5



Roboethics



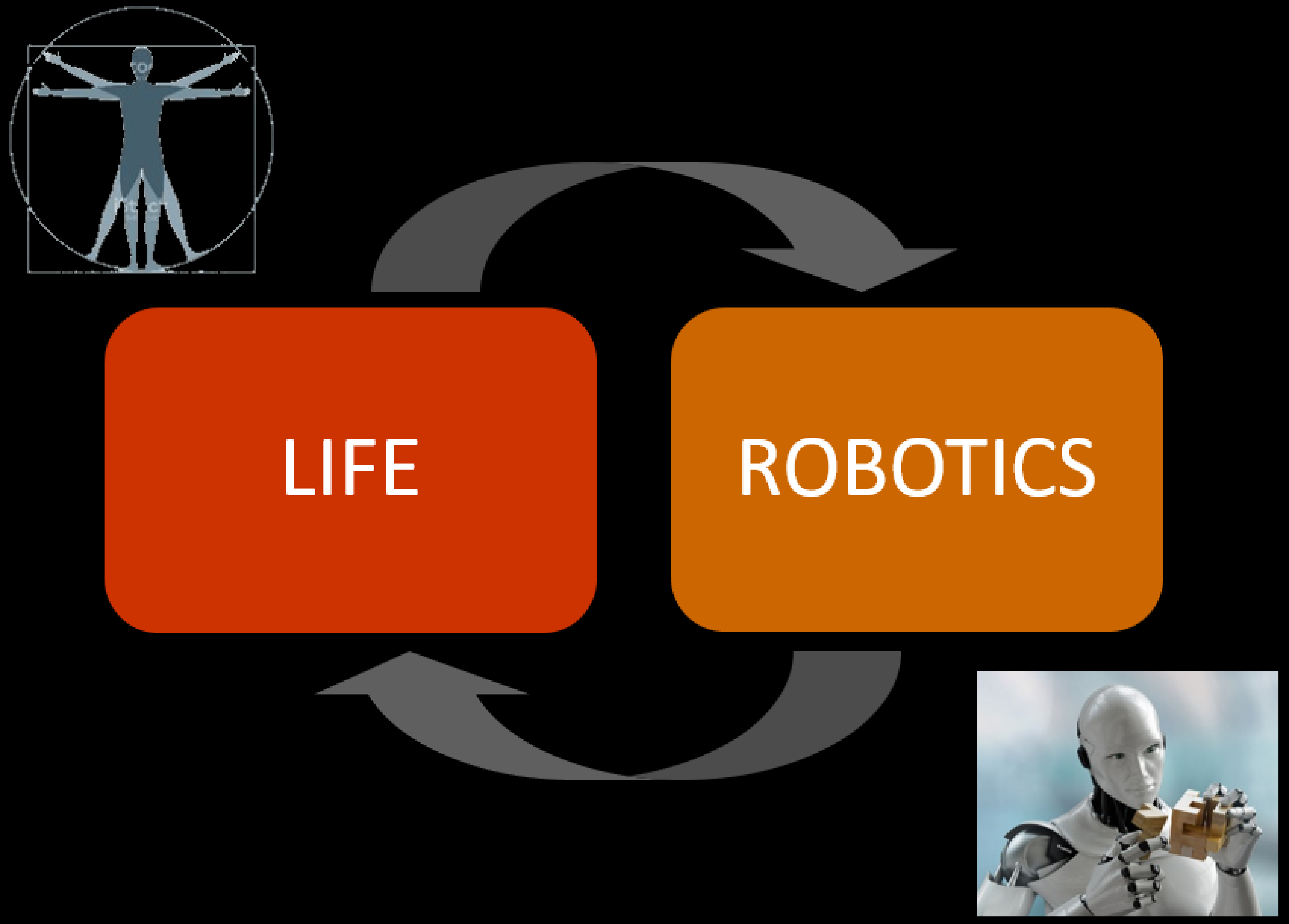
Ethical, legal, societal and economic (ELSE) issues for design, construction and use of robots

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*



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

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

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

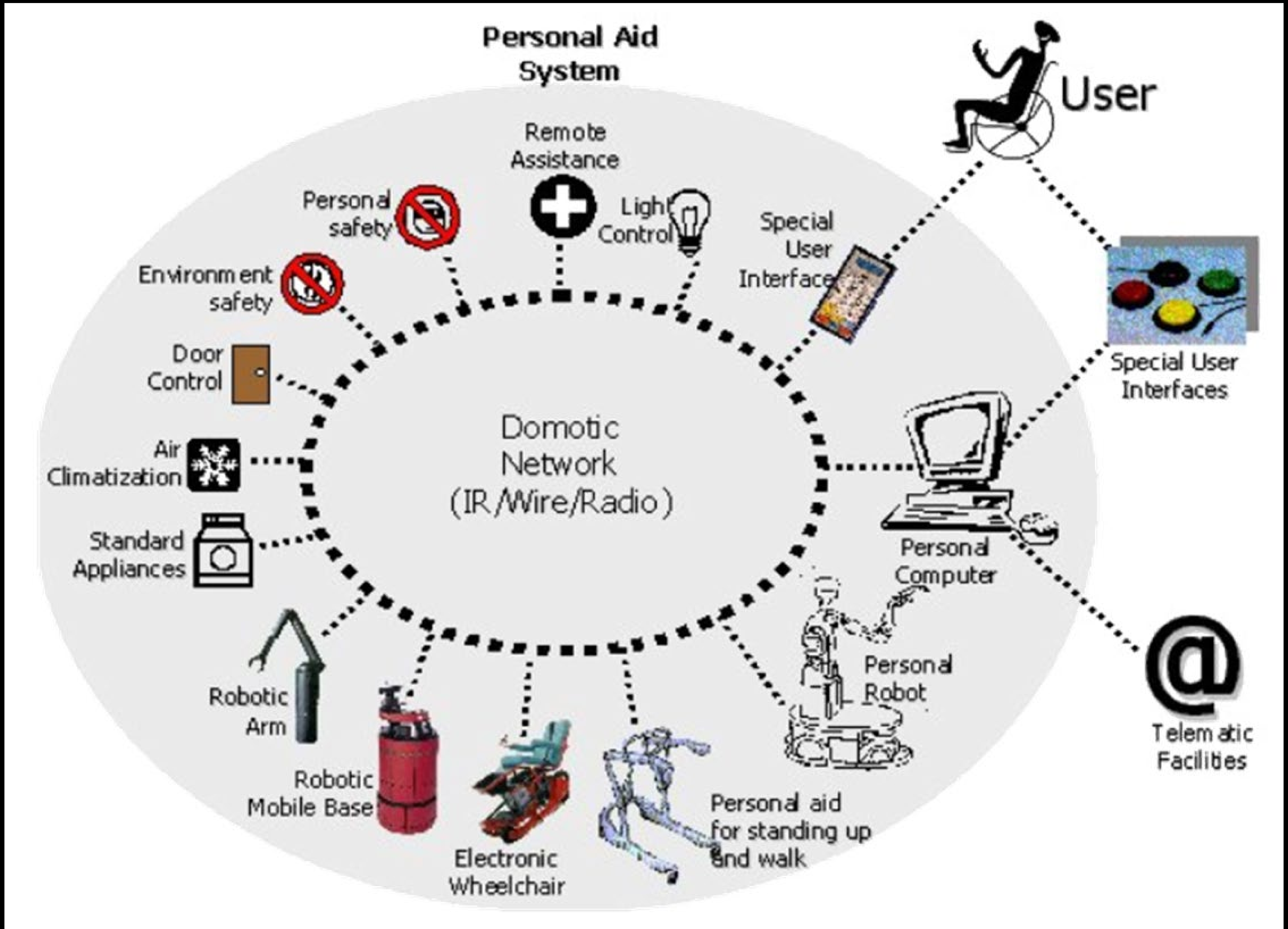
Future developments and expected growth of field largely depending on scientific cooperation

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)

The PRISMA Team

The ICAROS Center

Our Research Agenda

- ✓ *Aerial Robotics*
- ✓ *AI & Cognitive Robotics*
- ✓ *Dynamic and Legged Robotics*
- ✓ *Human–Robot Interaction*
- ✓ *Industrial Robotics*
- ✓ *Medical Robotics*

Our EU Research Projects

RoDyMan
SAPHARI
PHRIENDS
DEXMART
REFILLS
Harmony
ENDO THERANOSTICS

Manipulation & Interaction

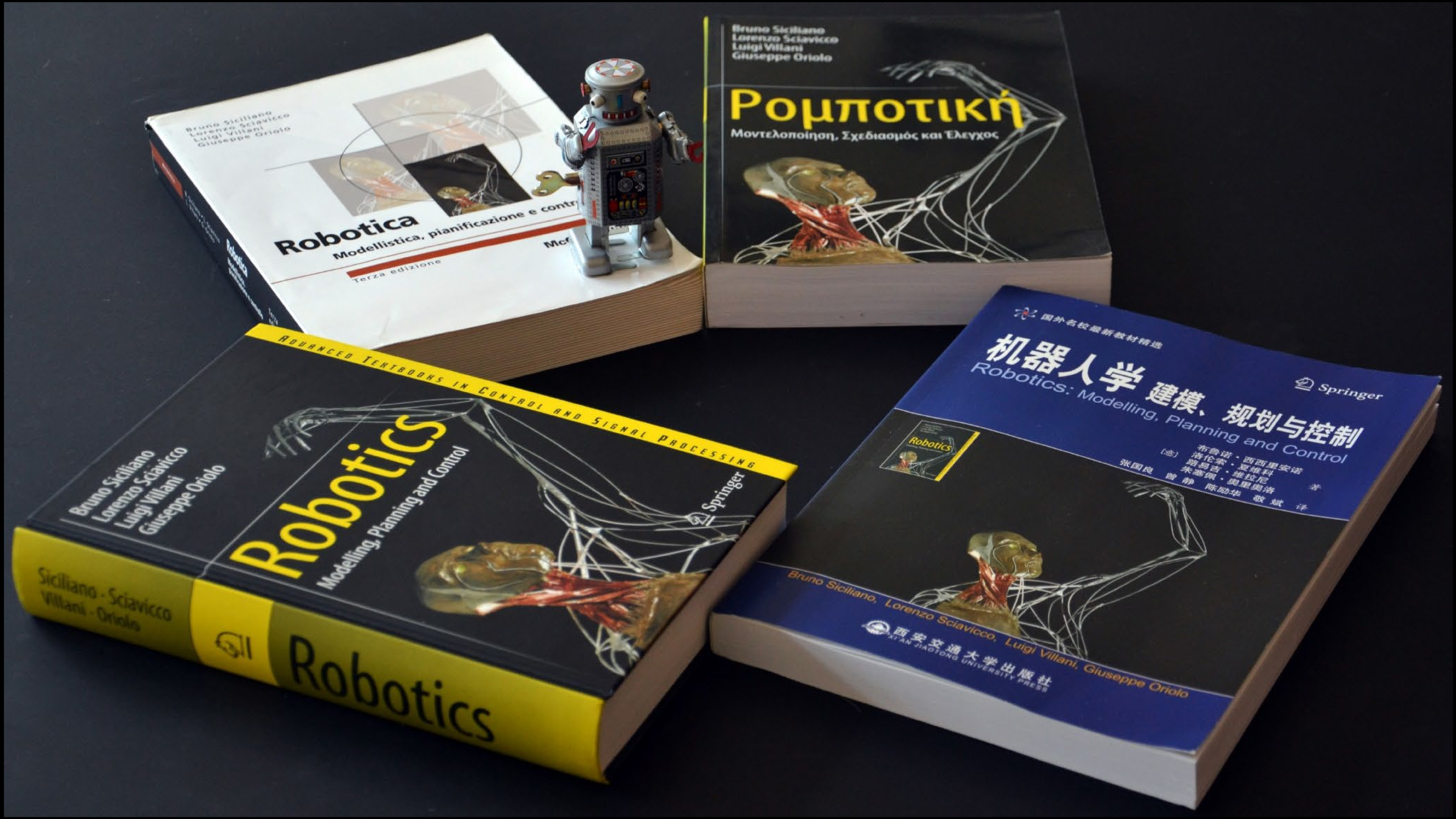
AIRobots
AEROARMS
AERIAL-CORE
SHERPA
ARCAS
HYFLIERS
AERO TRAIN

Aerial Robotics

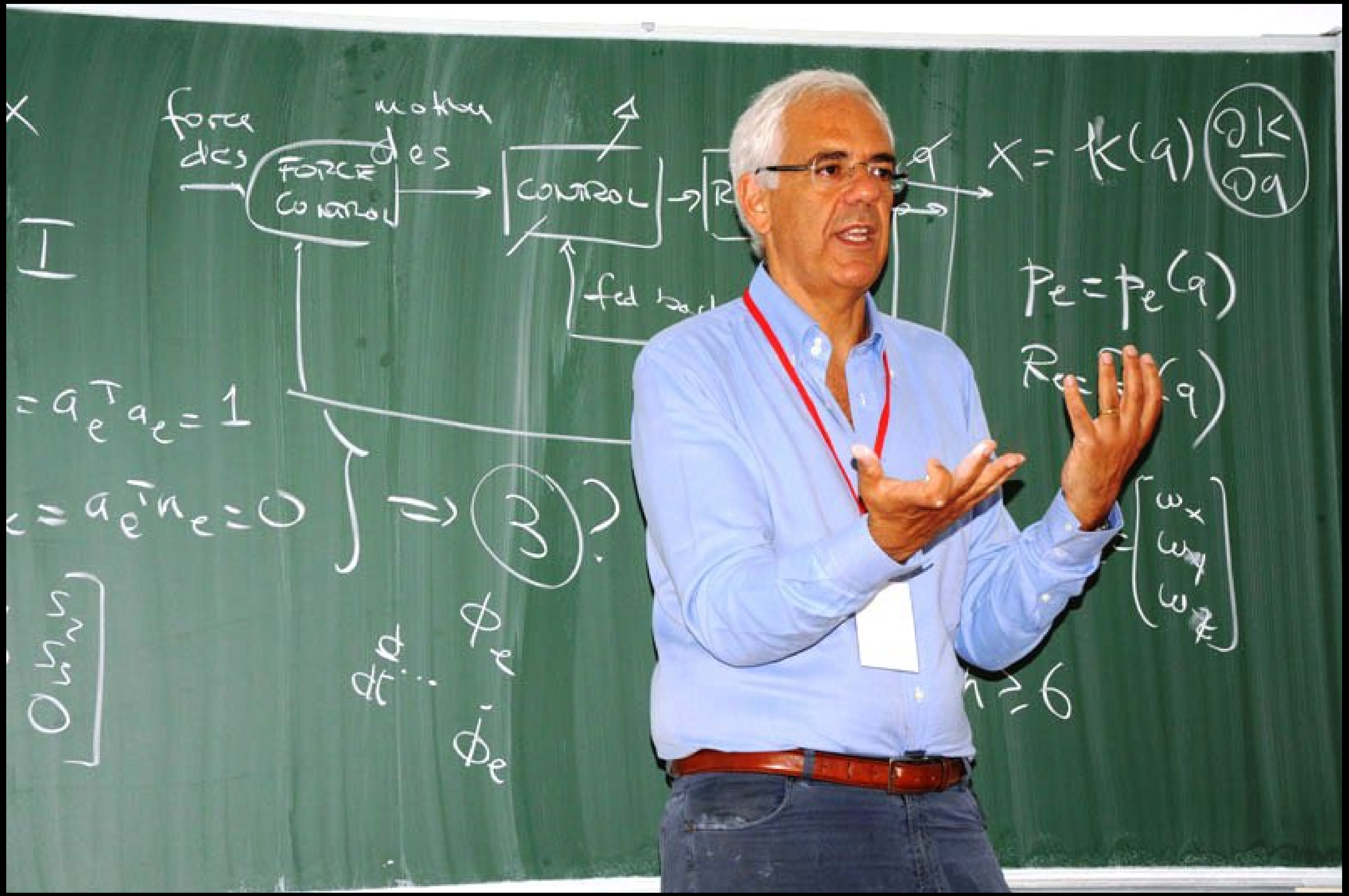
European ROBOTICS Research Network EURON
ROCK eu
ROCK eu²
eu Robotics
ethicbots
ECHORD
European Robotics Challenges
euROBIN
RIMA
DIH²

Networking & Technology Transfer

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*

Robotics as a New Science: The Handbook

Springer Handbook of Robotics

Editors: Bruno Siciliano, Oussama Khatib

Multimedia Editor: Torsten Kröger

SPRINGER NATURE

Bruno Siciliano *Editor*
Robotics Goes MOOC
Knowledge

The Robotics Goes MOOC project is organized in four volumes devoted to the paradigms of robotics: **knowledge**, **design**, **interaction**, **impact**.

The robot "concept" was clearly established by those many creative historical realizations, such as those recalled above. Nonetheless, the emergence of the "physical" robot had to await the advent of its underlying technologies of mechanics, controls, computers, electronics and sensors — in one word, mechatronics — during the course of the twentieth century. As always, new designs motivate new research and discoveries which, in turn, lead to enhanced solutions and thus to novel concepts. This virtuous circle over time produced that **knowledge** and understanding which gave birth to the field of Robotics, properly referred to as the science and technology of robots.

To make robots and intelligent machines useful to humans it is necessary to have a broad and tight intersection between Robotics and AI. Sophisticated mathematical models are needed that enable the robot from a physical point of view, as well as intelligent algorithms capable of correlating all the information coming from the use of technologically advanced sensors with the data available from experience. It is expected that the synergy of model-based techniques with data-driven approaches will contribute to increasing the level of autonomy of robots and intelligent machines in the near future.

The first book of the Robotics Goes MOOC project starts with the journey of robotics in the introductory chapter by Khatib, who has pioneered our field of robotics and has ferried it to the third millennium. Sensing is crucial for the development of intelligent and autonomous robots, as covered in Chapter 2 by Nüchter et al. Model-based control is dealt with in Chapter 3 by Kröeger et al along with motion planning, as well as in Chapter 4 by Villani and Chapter 5 by Chaumette to handle force and visual feedback, respectively, when interacting with the environment. Resorting to AI techniques is the focus of the last part of the book, namely, Chapter 6 by Peters et al on learning, Chapter 7 by Beetz et al on knowledge representation and reasoning, and Chapter 8 by Burgard et al on graph-based SLAM.

The content published here is linked to the *MOOC* course Robotics & Robots available at https://www.federica.eu/federica-pro/robotics-and-robots specifically created by Federica Web Learning, the Center for Innovation, Experimentation and Dissemination of Multimedia Education of University of Naples Federico II. You can access the related content via our app: download the Springer Nature *More Media* app for free, scan the link and access directly to the online course on your smartphone or tablet.

The image on the cover metaphorically illustrates the **knowledge** paradigm of robotics through a hand trying to catch an apple.

ISBN 978-3-319-74094-2
springer.com

Siciliano *Ed.*
Robotics Goes MOOC

Bruno Siciliano
Editor

Robotics Goes MOOC

Knowledge

MOREMEDIA

Springer

Bruno Siciliano *Editor*
Robotics Goes MOOC
Design

The Robotics Goes MOOC project is organized in four volumes devoted to the paradigms of robotics: **knowledge**, **design**, **interaction**, **impact**.

A robot's appearance and its way of interacting with humans is of fundamental importance. Until a few years ago there was a clear asymmetry between the typically excellent performance of industrial robots and their ugly and disharmonious bodies, with crude ways and potentially very dangerous movements for the human environment. A modern artifact can be as harmonious and beautiful as a complex biological machine or a work of plastic art and thus it should be clear how **design** plays a key role for robot technology to become a part of our everyday life and change it essentially in a responsible and beneficial manner. It is designers who shape the interface between humans and machines and, as such, they will contribute to make robots as customizable and intuitively useful to inexperienced users according to a plug-and-play mode.

The new concept of robotronics as the mechatronics approach to designing advanced robots is the focus of the first chapter of the second book of the Robotics Goes MOOC project by Asfour et al. The main issues for robot manipulator design are covered in the subsequent material, namely redundant robots in Chapter 2 by Maciejewsky et al and parallel robots in Chapter 3 by Müller, where widely adopted kinematic solutions are presented. Then, the adoption of flexibility, as opposed to the rigid mechanics paradigm, is discussed in Chapter 4 by Malzahn et al with reference to elastic robots and in Chapter 5 by Laschi focused on soft robotics. Somewhat speculating on the previous two design solutions comes Chapter 6 by Cutkosky dealing with bioinspired robots. The last part of the book is devoted to robot locomotion, namely, Chapter 7 by Vendittelli on wheeled robots and Chapter 8 by Harada on biped humanoids.

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The image on the cover metaphorically illustrates the **design** paradigm of robotics through a hand firmly grasping an apple.

ISBN 978-3-319-75822-0
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Editor

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Robotics Goes MOOC
Interaction

The Robotics Goes MOOC project is organized in four volumes devoted to the paradigms of robotics: **knowledge**, **design**, **interaction**, **impact**.

With the massive and pervasive diffusion of robotics technology in our society, we are heading towards a new type of a new type of a new type of AI, which we call physical AI at the intersection of Robotics with AI, that is the science of robots and intelligent machines performing a physical action to help humans in their jobs of daily lives. Physical assistance to disabled or elderly people; reduction of risks and fatigue at work; improvement of production processes of material goods and their sustainability; safety, efficiency and reduction of environmental impact in transportation of people and goods; progress of diagnostic and surgical techniques are all examples of scenarios where the new InterAction Technology (IAT) is indispensable.

The **interaction** between robots and humans must be managed in a safe and reliable manner. The robot becomes an ideal assistant, like the tool used by a surgeon, a craftsman, a skilled worker. The new generation of robots will co-exist — the cobots — with humans not only in the workplace but, gradually, in homes and communities, providing support in services, entertainment, education, health, manufacturing and care.

As discussed above, interaction plays a crucial role for the development of modern robotic systems. Grasping, manipulation and cooperative manipulators are covered in the first part of the third book of the Robotics Goes MOOC project, respectively in Chapter 1 by Prattichizzo et al, Chapter 2 by Kao et al, and Chapter 3 by Caccavale. Specific interaction issues along with the development of digital and physical interfaces are dealt with in Chapter 4 by Marchal et al and in Chapter 5 by Croft et al, respectively. Interaction between robot and human also means that a robot can be worn by a human as presented in Chapter 6 by Vitiello et al. A different type of interaction at a cognitive and planning level is the focus of Chapter 7 by Lima devoted to multi-robot systems and Chapter 8 by Song et al on networked, cloud and fog robotics, respectively.

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The image on the cover metaphorically illustrates the **interaction** paradigm of robotics through a hand dexterously manipulating an apple.

ISBN 978-3-319-77269-1
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Robotics Goes MOOC

Bruno Siciliano
Editor

Robotics Goes MOOC

Interaction

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Robotics Goes MOOC
Impact

The Robotics Goes MOOC project is organized in four volumes devoted to the paradigms of robotics: **knowledge**, **design**, **interaction**, **impact**.

It is often read in the media that AI and Robotics are the primary cause of technology unemployment. AI and machine learning techniques are expected to take over lower-level tasks, while humans can spend more time with higher-level tasks. In perspective, it can be said that jobs requiring boring cognitive tasks or repeatable and dangerous physical tasks will be considerably shredded by automation thanks to the wide adoption of AI and Robotics technology to replace humans, while jobs requiring challenging cognitive tasks or unstructured physical tasks will be suitably re-engineered with the progressive introduction of AI and Robotics technology to assist humans.

From the discussion above, it should be clear that in a world populated by humans and robots, issues arise that go beyond engineering and technology due to the **impact** resulting from the use of robots in various application scenarios. The anthropization of robots cannot ignore the resolution of those ethical, legal, social, economic (ELSE) problems that have so far slowed their spread in our society.

The final book of the Robotics Goes MOOC project enlightens the impact of using robotic technology in the main fields of application, namely, industrial robots as in Chapter 1 by Bischoff et al, medical robotics as in Chapter 2 by Dario et al, aerial robots as in Chapter 3 by Ollero et al, orbital robotics as in Chapter 4 by Lampariello, underwater robots in Chapter 5 by Antonelli, and rescue robots as in Chapter 6 by Murphy. The last part is devoted to the open dilemma of using and accepting robots in human co-habited environments which is addressed in Chapter 7 on social robotics by Pandey and the very final chapter by Tamburrini on the important issues raised with roboethics.

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The image on the cover metaphorically illustrates the **impact** paradigm of robotics through a hand holding bitten an apple.

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