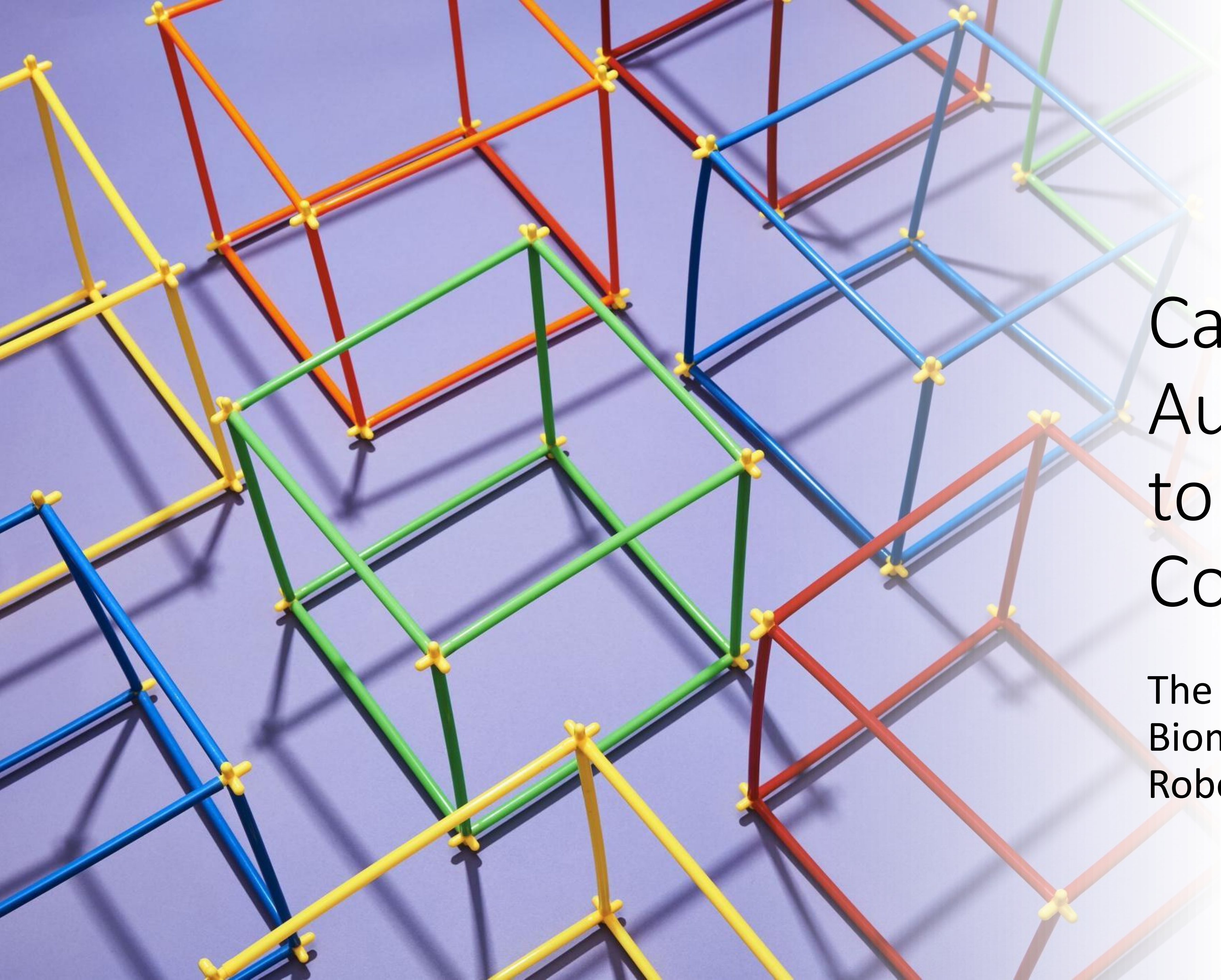


Caged Automation to True Collaboration

The New Reality of Biomimicry & Human–Robot Collaboration

Introduction

- THE INDUSTRIAL AUTOMATION LANDSCAPE IS UNDERGOING A MAJOR SHIFT
- ROBOTS ARE NO LONGER ISOLATED TOOLS BUT COLLABORATIVE PARTNERS
- BIOMIMICRY AND BIOLOGICAL INTELLIGENCE ARE REDEFINING ROBOT DESIGN
- HUMAN-CENTERED AUTOMATION ALIGNS WITH INDUSTRY 5.0 VALUES
- INTERDISCIPLINARY KNOWLEDGE ACROSS STEM IS CRITICAL

Industrial Revolutions

Late 18th century

FIRST INDUSTRIAL REVOLUTION

Steam Engine, Machinery-based production, Textile Industry

Late 19th century

SECOND INDSUTRIAL REVOLUTION

Electric Power, Steel production, Oil and petroleum

Late 20th century

THIRD INDUSTRIAL REVOLUTION

Digital Technologies, Semiconductor, Automation,

Early 2010s

FOURTH INDUSTRIAL REVOLUTION

Artificial Intelligence, Cloud Computing, Cybersecuritywhen and

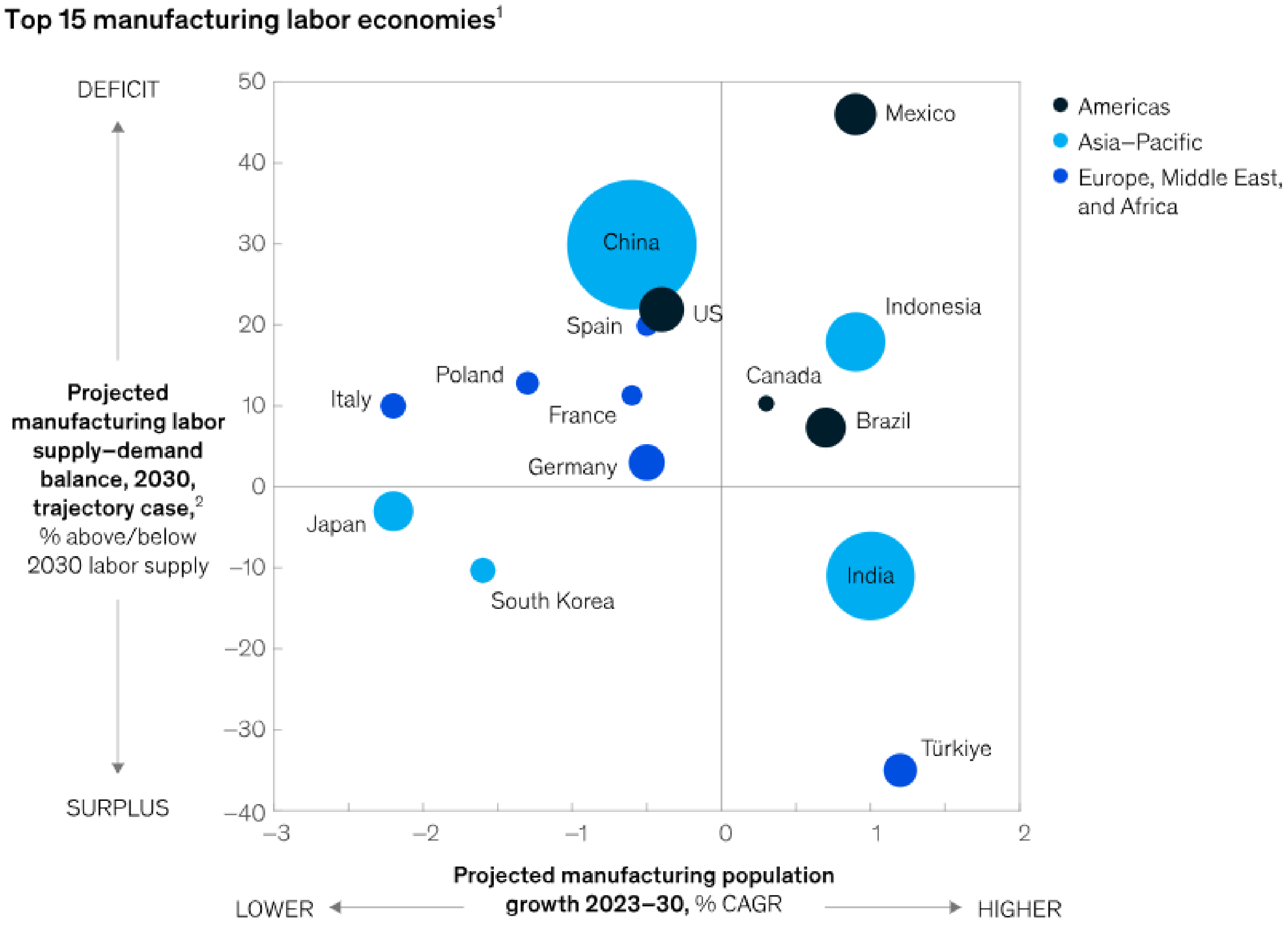
Labor supply challenges

the US BLS reported 622,000 unfilled manufacturing job openings, while overall labor force participation rate fell from 67% in the 1990s to below 63% in 2023.

2030

Jan. 2024

manufacturing could face a shortage of 1.5 million to 2.5 million workers by 2030, according to McKinsey analysis.



[1]Defined by total number of manufacturing workers reported in 2023.
[2]The y-axis is calculated as the % difference between future demand and future supply for full-time talent. Both supply and demand for talent are calculated from historical growth rates in productivity, manufacturing-sector demand, and manufacturing-sector workforce participation.
Source: World Bank

Evolution of Industrial Robotics

- 1961 — Unimate: the first industrial robot
- Early systems required fixed programming and physical fences
- 1980s–2000s: High-speed, high-power, rigid robots dominate automotive
- 2010s: Rise of collaborative robots (cobots)
- Today: Robots with perception, AI, learning, and safe interaction

What Is Caged Automation?

Robots separated by:

- metal fences
- light curtains
- pressure-sensitive mats

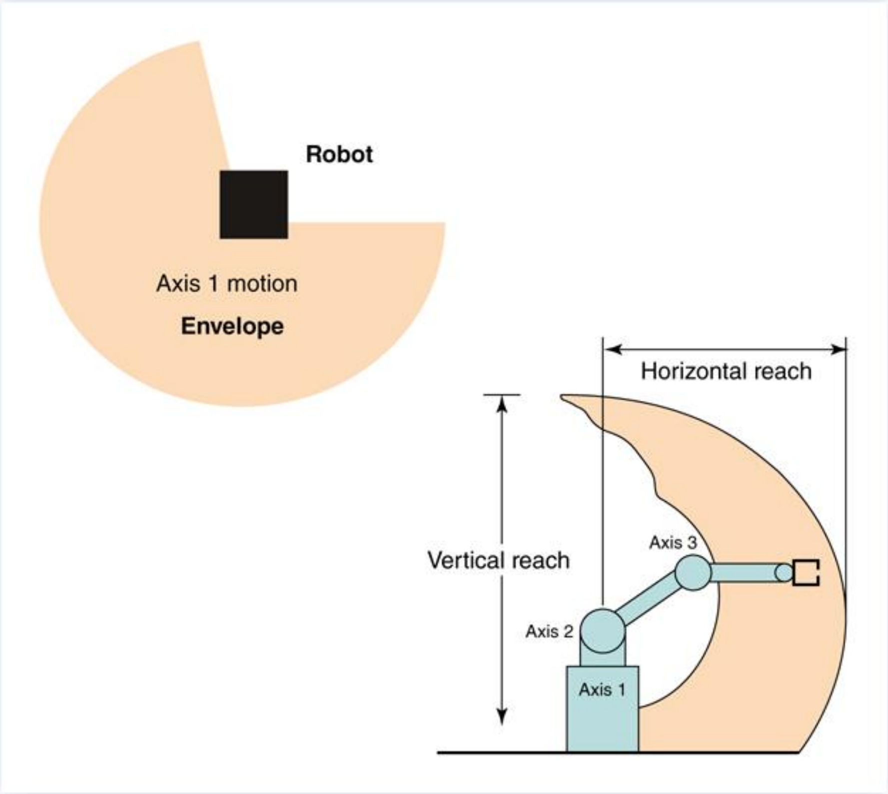
Required due to high forces and unpredictable motion

Humans and robots could not share a workspace

Result: limited flexibility and high changeover times

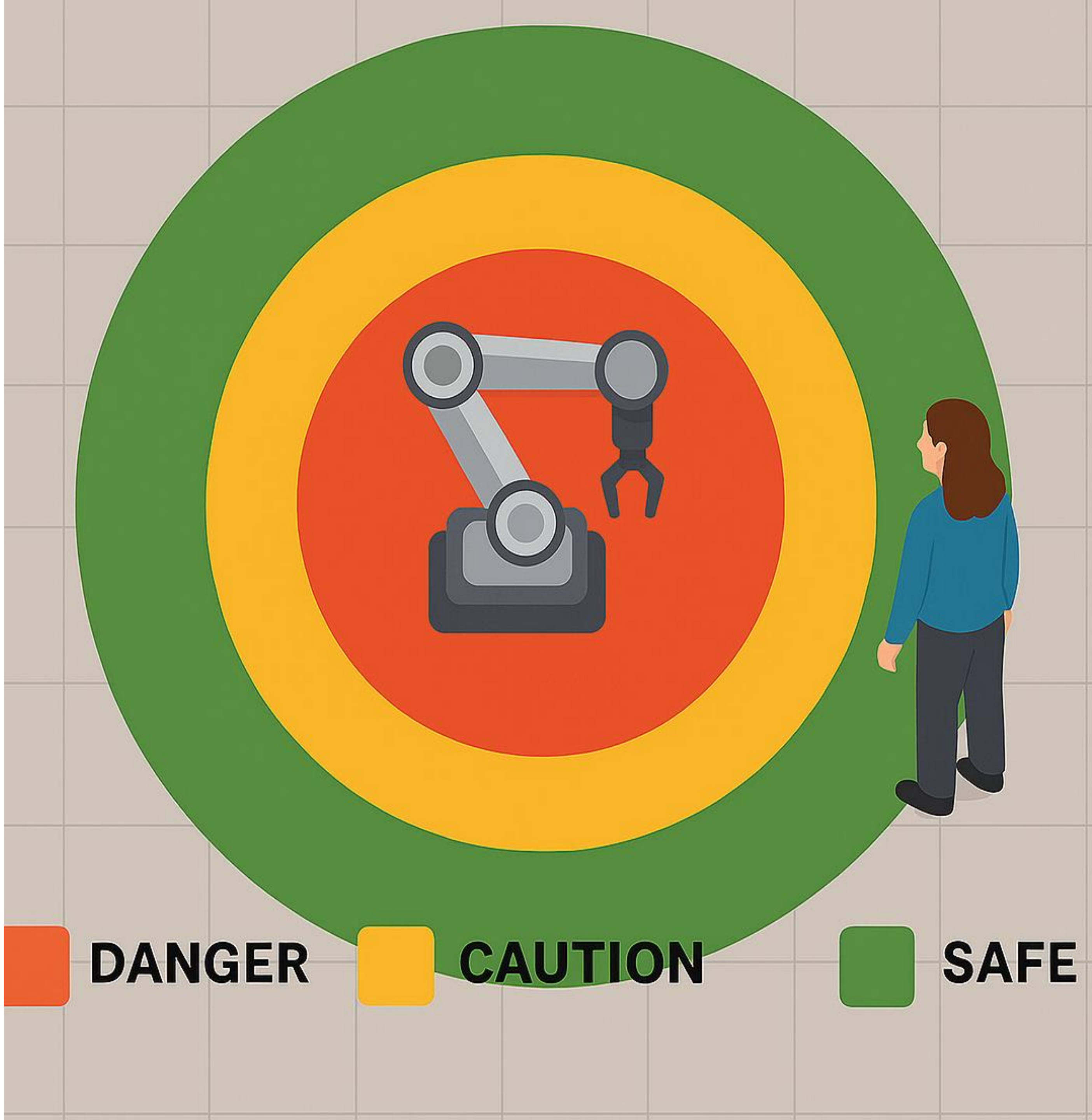
Safety achieved by physical distance, not technological intelligence

6-axis Articulated Robot



Limitations of Traditional Robots

- Inflexible and require re-programming for new tasks
- Not aware of surroundings — blind systems
- Could injure workers due to force and speed
- High cost of safety guarding and floor space
- Incompatible with modern high-mix, low-volume manufacturing



Introduction to Human–Robot Collaboration (HRC)

Cobots: designed for close human interaction

Power & Force Limiting (PFL) ensures injury prevention

Robots become responsive to human proximity

Humans and robots share tasks — not isolated workflows

Designed for high flexibility, low setup time

Why Human–Robot Collaboration Now?

Global labor shortages in manufacturing and logistics

Increased demand for small-batch, customizable production

Advances in AI perception, sensing, and control

Push toward sustainable and human-centric Industry 5.0

Growing accessibility of cobots (affordable, easy to program)

Biomimicry: A New Paradigm

- Nature-inspired mechanisms improve robot adaptability
- Organisms offer models for gripping, movement, sensing
- Efficiency in natural systems reduces energy use
- Biomimetic control mimics human or animal motion
- Enhances safety via more natural, predictable movement patterns

Biomimetic Robotics Examples

Octopus tentacle-inspired soft arms:

- Flexible, compliant, inherently safe

Gecko-inspired adhesive grippers:

- Zero-pressure gripping for delicate surfaces

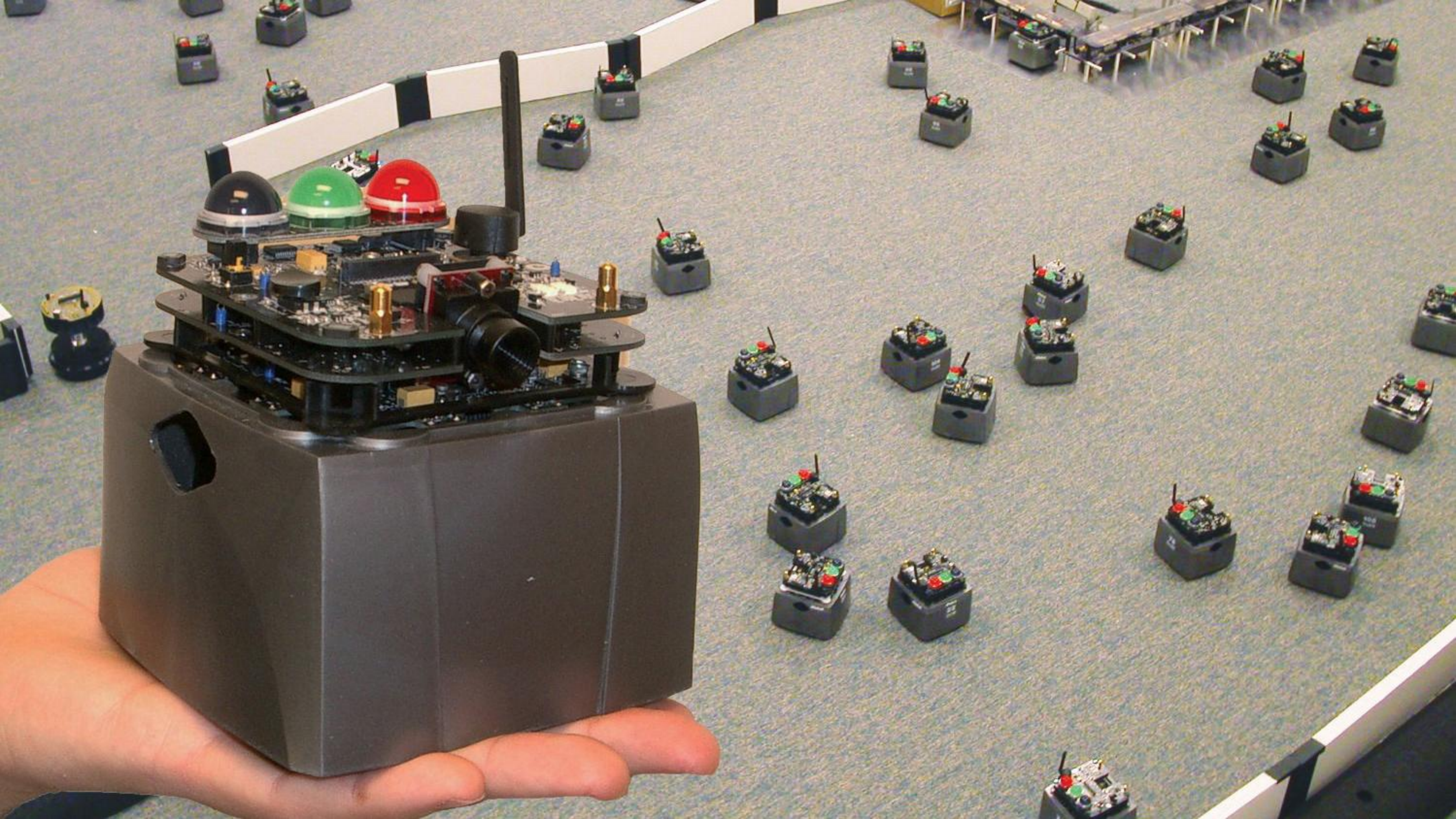
Fish-inspired underwater robots:

- Highly maneuverable and silent

Ant inspired swarm robotics:

- Coordination without centralized control

Bird-inspired flight and balance mechanisms



Industry 4.0 ? Industry 5.0

Industry 4.0:

- Automation, IoT, cyber-physical systems

Industry 5.0:

- Human-centric, sustainable, resilient
- Robots augmenting human intelligence

Humans + robots: synergistic collaborators

Emphasis on personalization and adaptability

Human-Centric Automation

- Technology designed around human capability
- Robots relieve humans from repetitive/ergonomic tasks
- Workers focus on creativity, decision-making, and oversight
- Integration of ergonomics, safety psychology, and human factors
- Better job satisfaction and workplace well-being

Safety Innovations Enabling HRC

- Power and force limiting mechanisms prevent injury
- Speed and separation monitoring using sensors
- AI-based dynamic safety zones
- Built-in torque sensors for safe contact
- Safety-rated monitored stops integrated into robot firmware

ISO/TS 15066 Overview

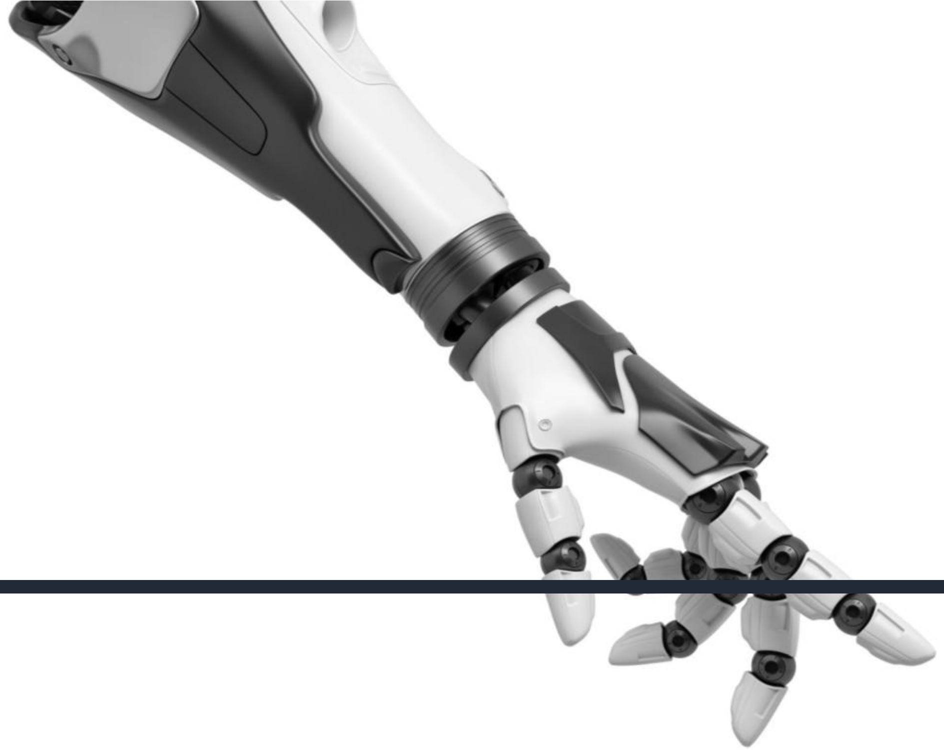
Defines safe limits for human–robot collaborative operations

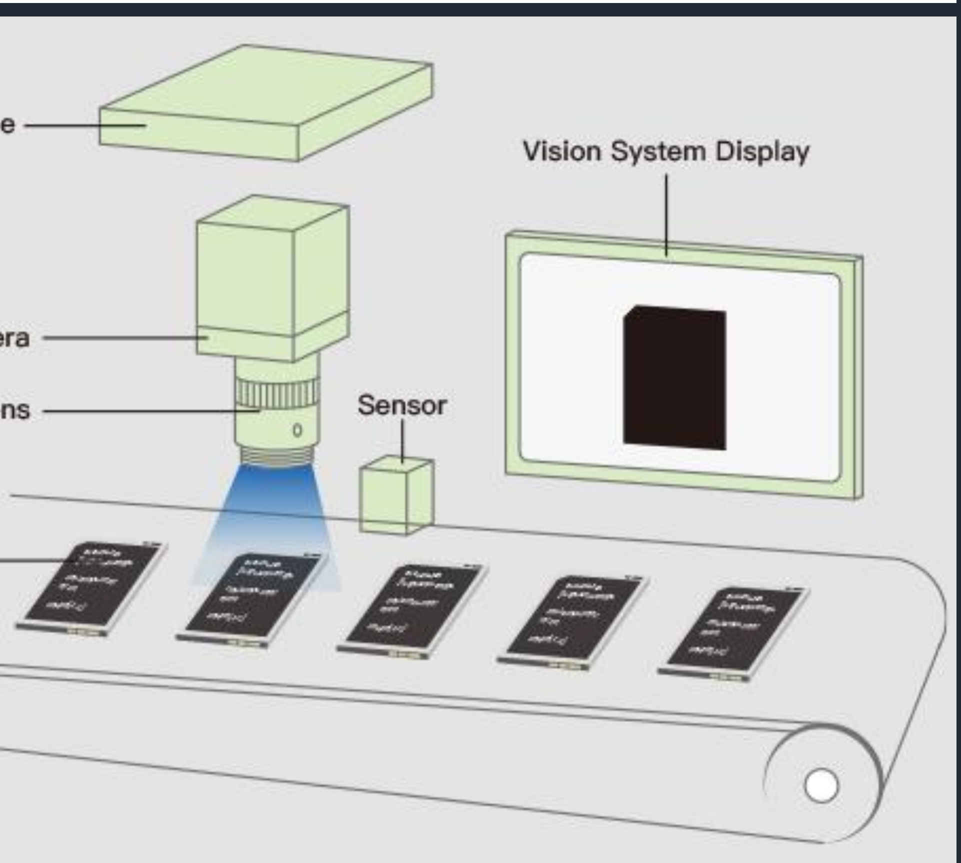
Provides quantitative pain thresholds for body regions

Specifies requirements for:

- Power & Force Limiting (PFL) – robots must limit force to avoid injury.
- Speed & Separation Monitoring (SSM) – dynamic safety zones based on proximity.
- Hand-guiding mode – safe manual control of robots.
- Safety-rated monitored stops – emergency stop integrated into firmware.

AI & Perception in Modern Robots





- Vision systems detect human presence & gestures
- 3D cameras enable spatial understanding
- Machine learning improves movement prediction
- AI adapts robot trajectories to human behavior
- Multi-modal perception: vision, force, audio, proximity

Soft Robotics & Compliance

- Materials: silicone, polymers, textiles, electroactive materials
- Movement inspired by muscles, tendons, or soft organisms
- High compliance makes robots inherently safe
- Ideal for handling food, biological samples, delicate components
- Bridges the gap between rigid robotics and natural motion

Collaborative Robot Use Cases

- Light assembly & finishing
- Machine tending for CNC mills/lathes
- Pick-and-place for packaging
- Lab automation: pipetting, sorting, analysis
- Educational training tools
- Medical applications (assistive robotics)

Adaptive Automation

Robots adjust behavior in real-time:

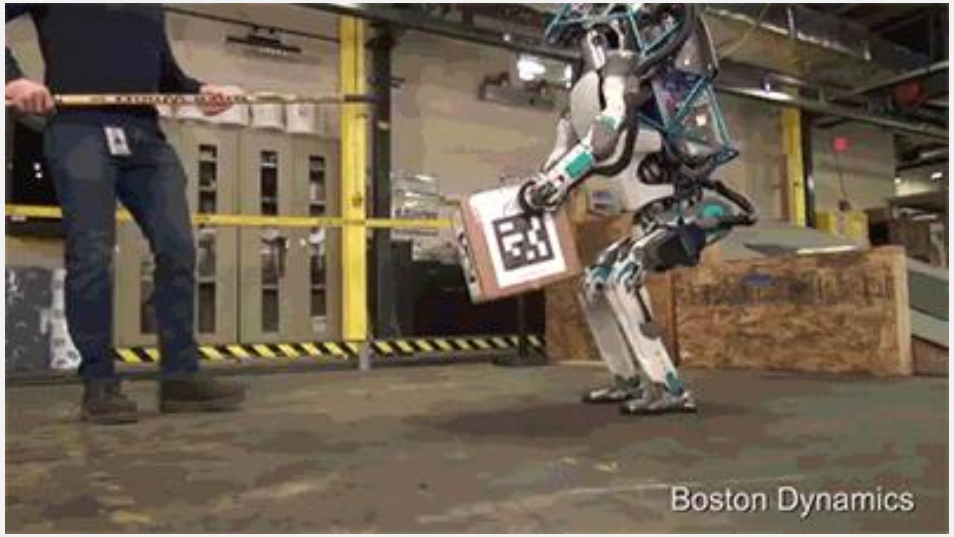
- speed
- direction
- force

AI-driven intent recognition

Customization at the point of need

Enables “mass customization” manufacturing workflows

Robots become flexible team members



Cognitive & Neuroadaptive Interfaces

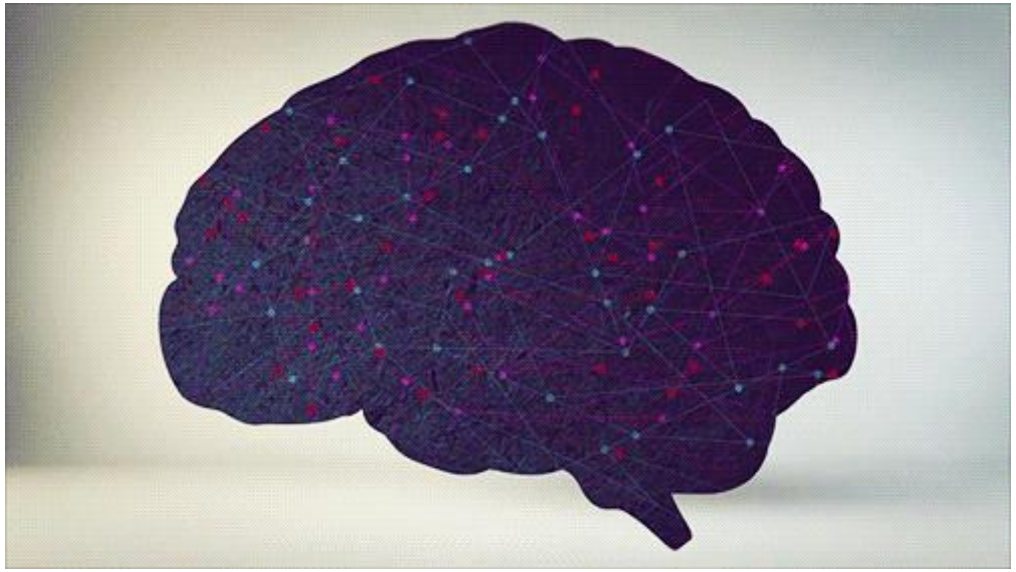
EEG-based brain-computer interfaces for robot control

Detecting cognitive load or fatigue

Robots pause or slow down when user stress rises

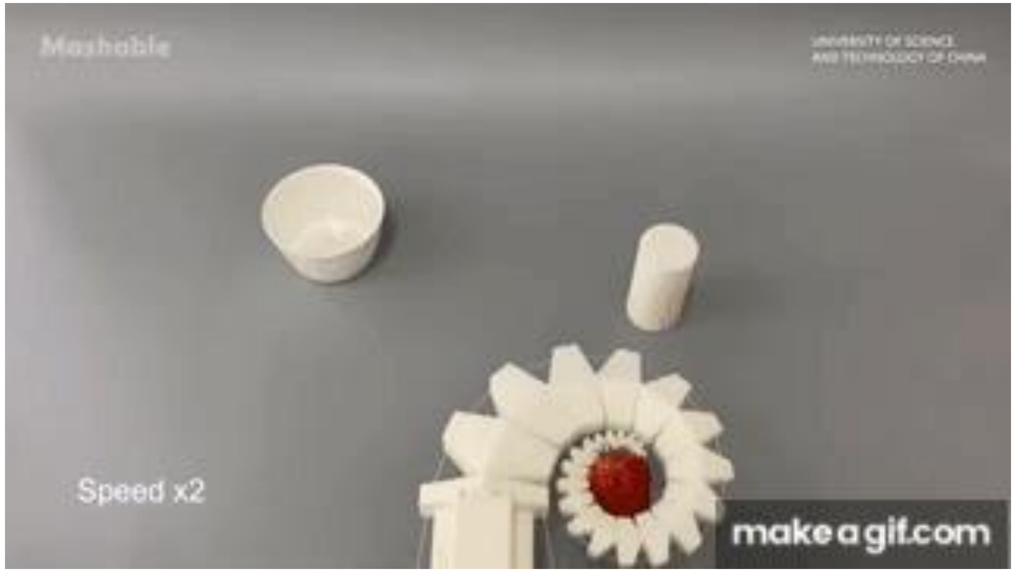
Attention-based control reduces errors

Integration with AR/VR instruction systems



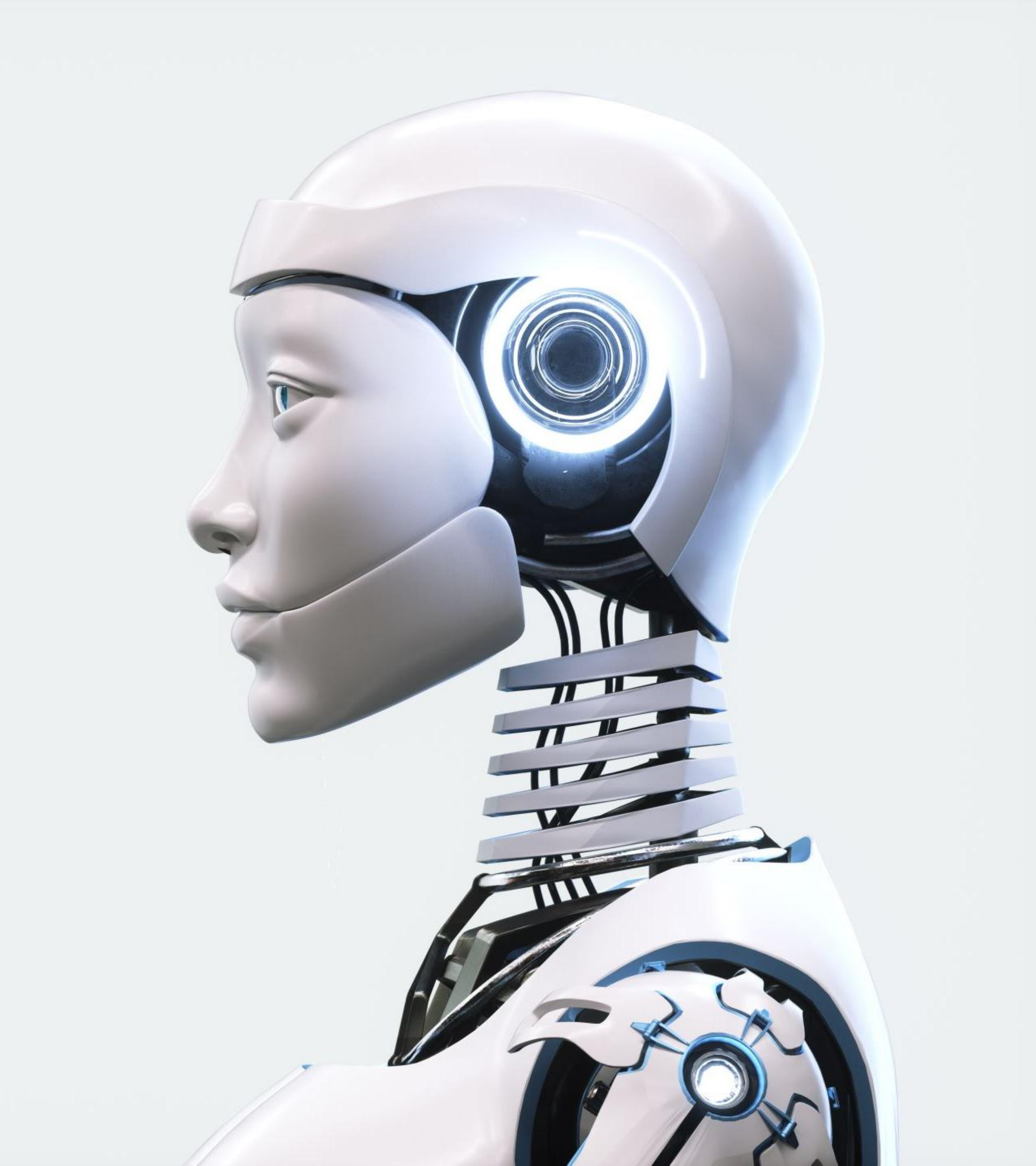
Sensing Human Intention

- Eye gaze tracking to predict tasks
- Gesture recognition using cameras
- EMG (muscle signals) for exoskeletons and control
- Motion prediction algorithms forecast human trajectories
- Robots pre-plan to avoid collision or assist proactively



Biomimicry + AI Synergy

- Natural movement patterns & intuitive robot behavior
- AI perception reduces unpredictable motion
- Robots learn human preferences
- Safety through prediction rather than reaction
- Nature-inspired intelligence integrated with deep learning



Biology & Chemistry Examples

- Robots pipetting with precision beyond human capability
- Handling fragile biological samples
- Microfluidic automation
- Biomechanics driving exoskeleton design
- Automated chemical mixing and analysis

Physics & Computer Science Examples

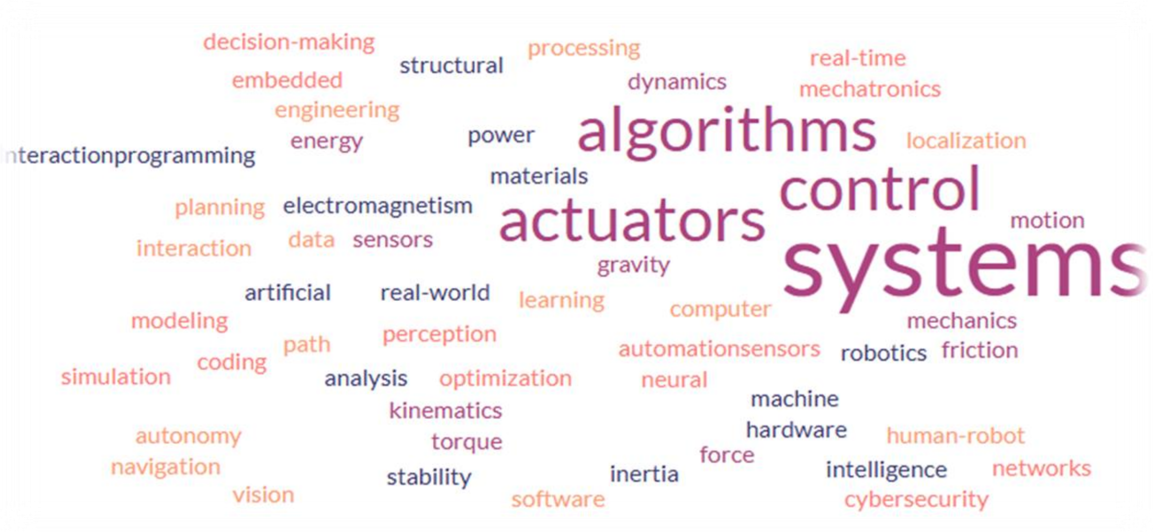
Physics concepts applied to dynamic control systems

Vibration control, rigid body dynamics, safety limits

Computer Science enables:

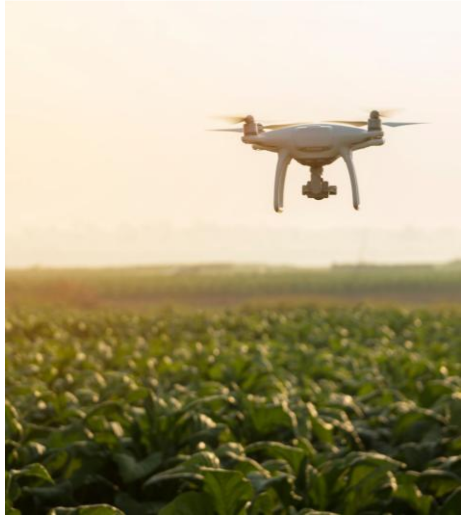
- machine vision
- AI decision-making
- reinforcement learning
- simulation and digital twins

Algorithms predict safe robot-human interaction



Agriculture Applications

- Greenhouse monitoring with robot arms
- Selective harvesting robots
- Soil quality and moisture scanning
- Drone-based crop analysis
- Cobots for sorting and packing produce



Workforce & Education Impact

- Need for new HRC safety competencies
- Students require programming + human factors understanding
- Interdisciplinary curriculum becoming essential
- Upskilling existing workforce
- Robots as co-workers during labs and internships

Challenges

- Cost of advanced sensors and AI integration
- Training faculty and staff
- Organizational resistance to new processes
- Safety and liability concerns
- Data security and cyber-physical vulnerabilities

Future Trends

- Exoskeletons enhancing human strength and endurance
- Swarm robotics for logistics and agriculture
- Semi-autonomous cognitive robots
- Biohybrid robots incorporating living cells
- Real-time neuroadaptive safety systems

Conclusion

- The shift from caged to collaborative automation is transformative
- Biomimicry expands what robots can safely and intuitively do
- HRC requires interdisciplinary STEM engagement
- The future is human-centered, adaptive, and intelligent
- Our role is to prepare students and research teams for this future

Discussion

- Where can your discipline intersect with biomimicry or human–robot collaboration?
- What natural phenomena inspire solutions in your field?
- What interdisciplinary projects could we start this year?
- How could robots assist or collaborate in your labs?