CS65K Robotics

Modelling, Planning and Control

Chapter 1 Introduction

LECTURE 2: INDUSTRIAL AND ADVANCED ROBOTS

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IEEE SENIOR MEMBER

Overview

- Data regarding installations and supply of industrial robots worldwide are presented
- Typical applications for a manufaturing process are surveyed
- A number of industrial robots are illustrated in terms of their features and application fields

Industrial Robots

SECTION 1

Industrial Robotics

Industrial robotics ≡ discipline concerning robot design, control and applications in industry

- Its products have by now reached the level of a mature technology
- Industrial robots operate in a structured environment (geometrical or physical characteristics mostly known a priori)

Industrial Robotics

Early industrial robots developed in the 1960s at confluence of two technologies

- Numerical control machines for precise manufacturing
- Teleoperators for remote radioactive material handling

Industrial Robotics

Features

Versatility (employment of different end-effectors at manipulator's tip)

Adaptability to a priori unknown situations (use of sensors)

Positioning accuracy (adoption of feedback control techniques)

Execution repeatability (programmability of various operations)

Industrial Robot and Automation

SECTION 2

Industrial Robot and Automation

EA robot is a reprogrammable multifunctional manipulator designed to move materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks (Robot Institute of America, 1980).

Industrial Robot and Automation

Industrial robot ≡ machine with high versatility and flexibility $\Longrightarrow$ Typical component of programmable automated systems in wide range of applications

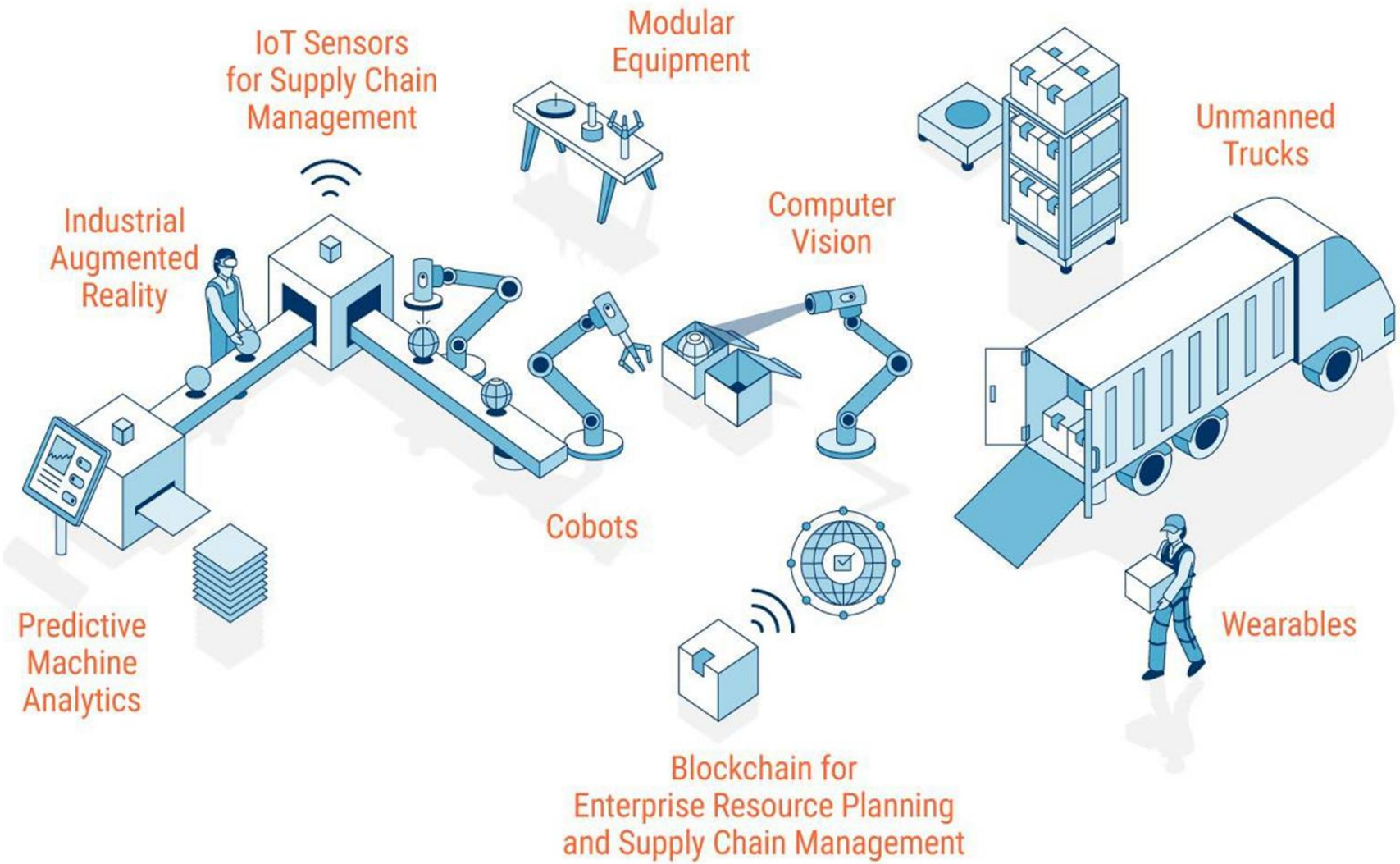
- Reduction of manufacturing costs
- Increase of productivity
- Improvement of product quality standards
- Possibility of eliminating harmful or off-putting tasks for human operator

Industrial Robot and Automation

Automation ≡ technology aimed at replacing human beings with machines in a manufacturing process, as regards not only execution of physical operations but also intelligent processing of information on status of process.

Industrial Robot and Automation

- Rigid automation ≡ mass manufacture of products of same type
- Programmable automation manufacture of low-to-medium batches of products of different types
- Flexible automation manufacture of variable batches of different products


IoT Sensors
for Supply Chain
Management
Modular
Equipment
Unmanned
Trucks
Industrial
Augmented
Reality
Computer
Vision
Cobots
Predictive
Machine
Analytics
Wearables
Blockchain for
Enterprise Resource Planning
and Supply Chain Management

Material Handling

- Transportation of objects from one location in the factory to another in order to be stored, manufactured, assembled, and packed
- Palletizing (placing objects on a pallet in an ordered way)
  - Warehouse loading and unloading
  - Mill and machine tool tending
  - Part sorting
  - Packaging

Examples of AGVs for material handling (courtesy of E&K Automation GmbH)

Manipulation

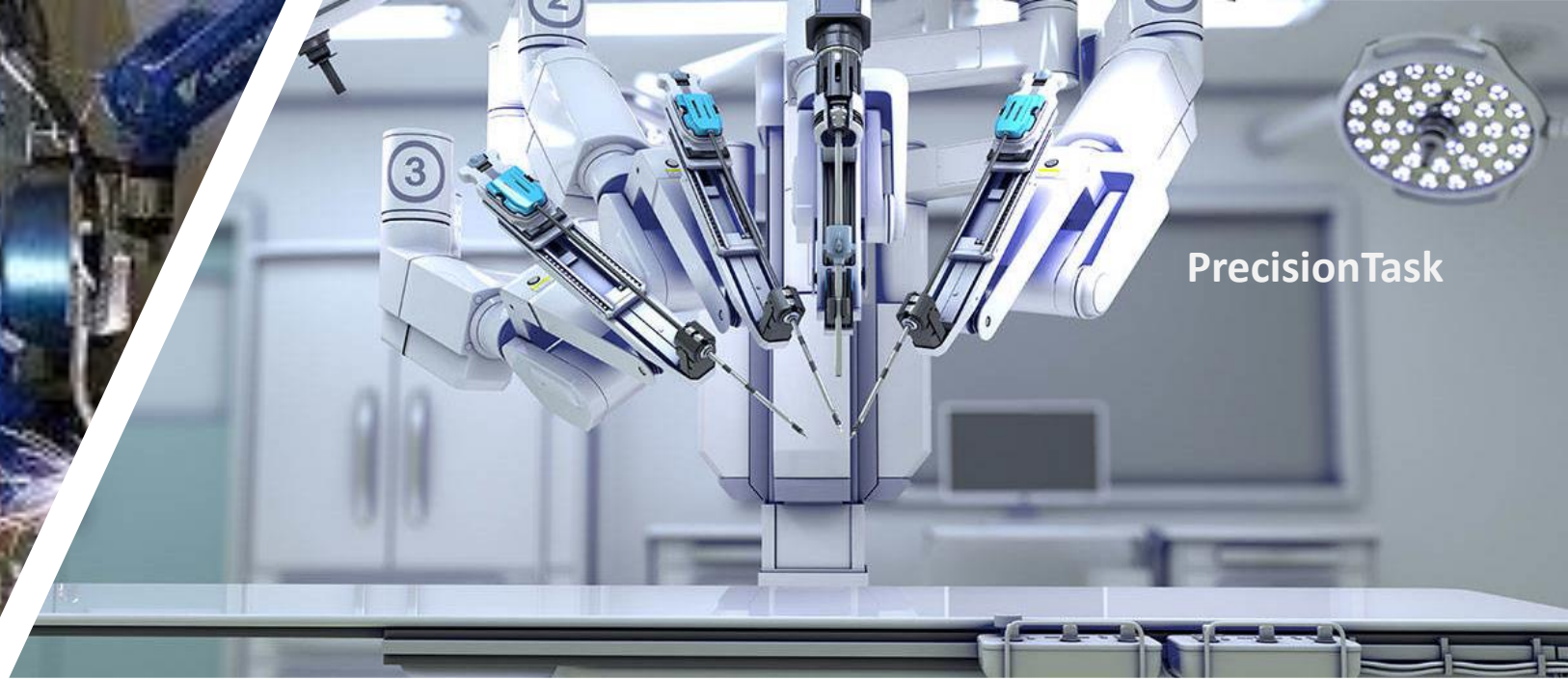
Transforming objects from raw material into finished products

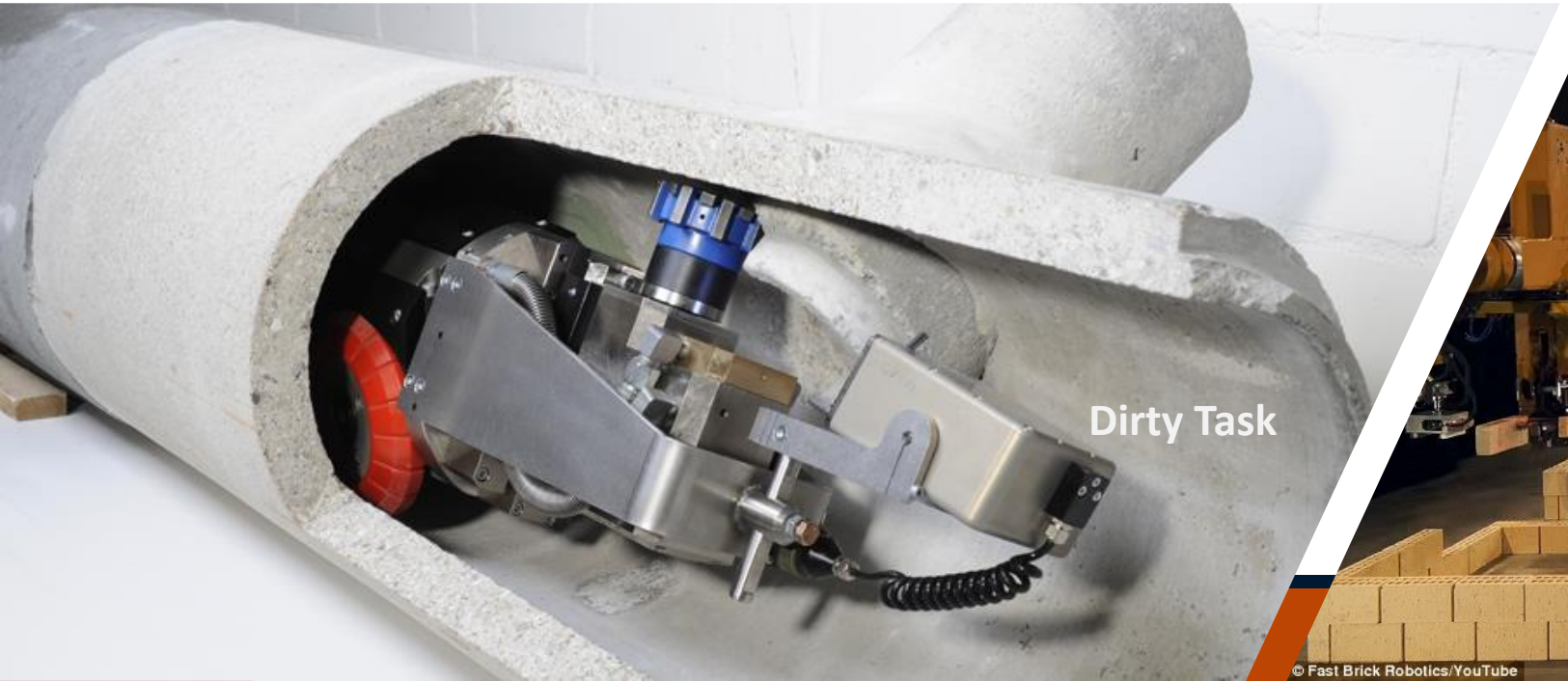
- Arc and spot welding
- Painting and coating
- Gluing and sealing
- Laser and water jet cutting
- Milling and drilling
- Casting and die spraying
- Deburring and grinding
- Screwing, wiring and fastening
- Assembly of mechanical and electrical groups
- Assembly of electronic boards

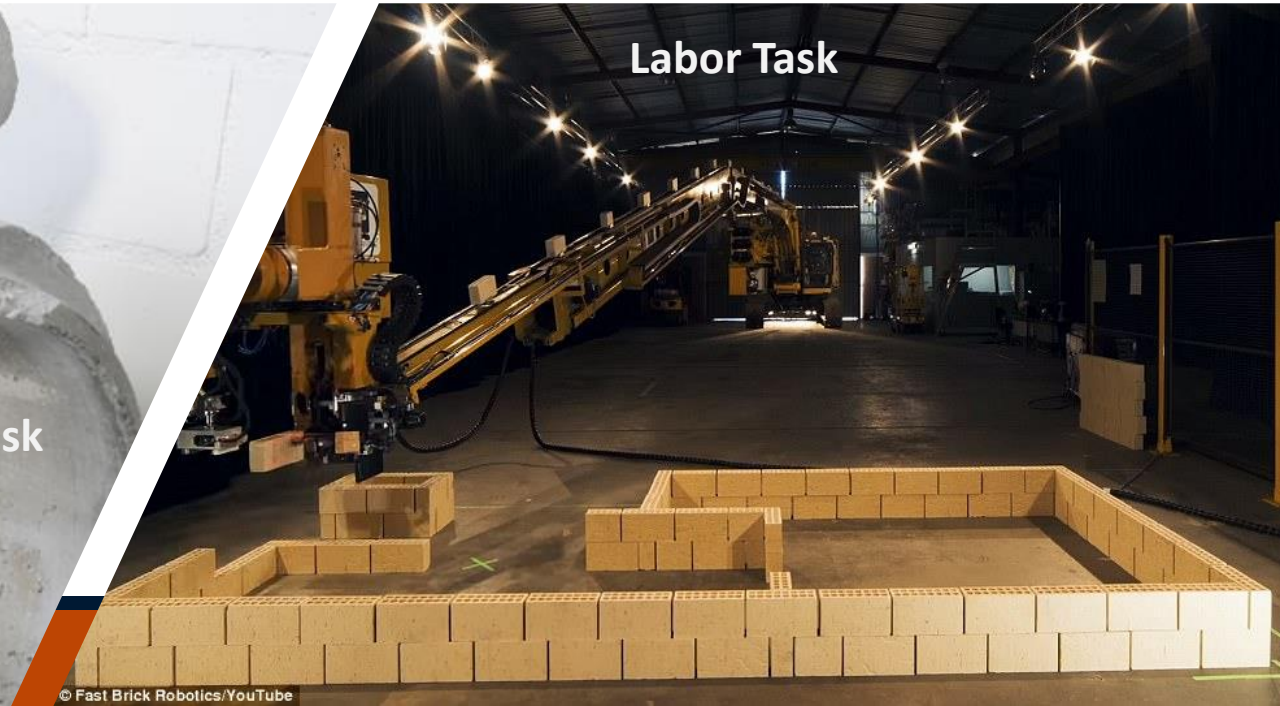
Besides material handling and manipulation, in a manufacturing process it is necessary to perform measurements to test product quality

- Object inspection
- Contour finding
- Detection of manufacturing imperfections

Dangerous Task


PrecisionTask


Dirty Task


Labor Task
© Fast Brick Robotics/YouTube

World Statistics

SECTION 3

World Statistics

Data up to 12/2013 (Annual report by International Federation of Robotics)

- 1.3÷1.6 million of robots at work worldwide
- Most successful year for industrial robots since 1961
- Total market of 9.5 billion $ (+12%)
- Estimated market of 29 billion $
- Largest markets: Japan, China, USA, Korea, Germany (70%)

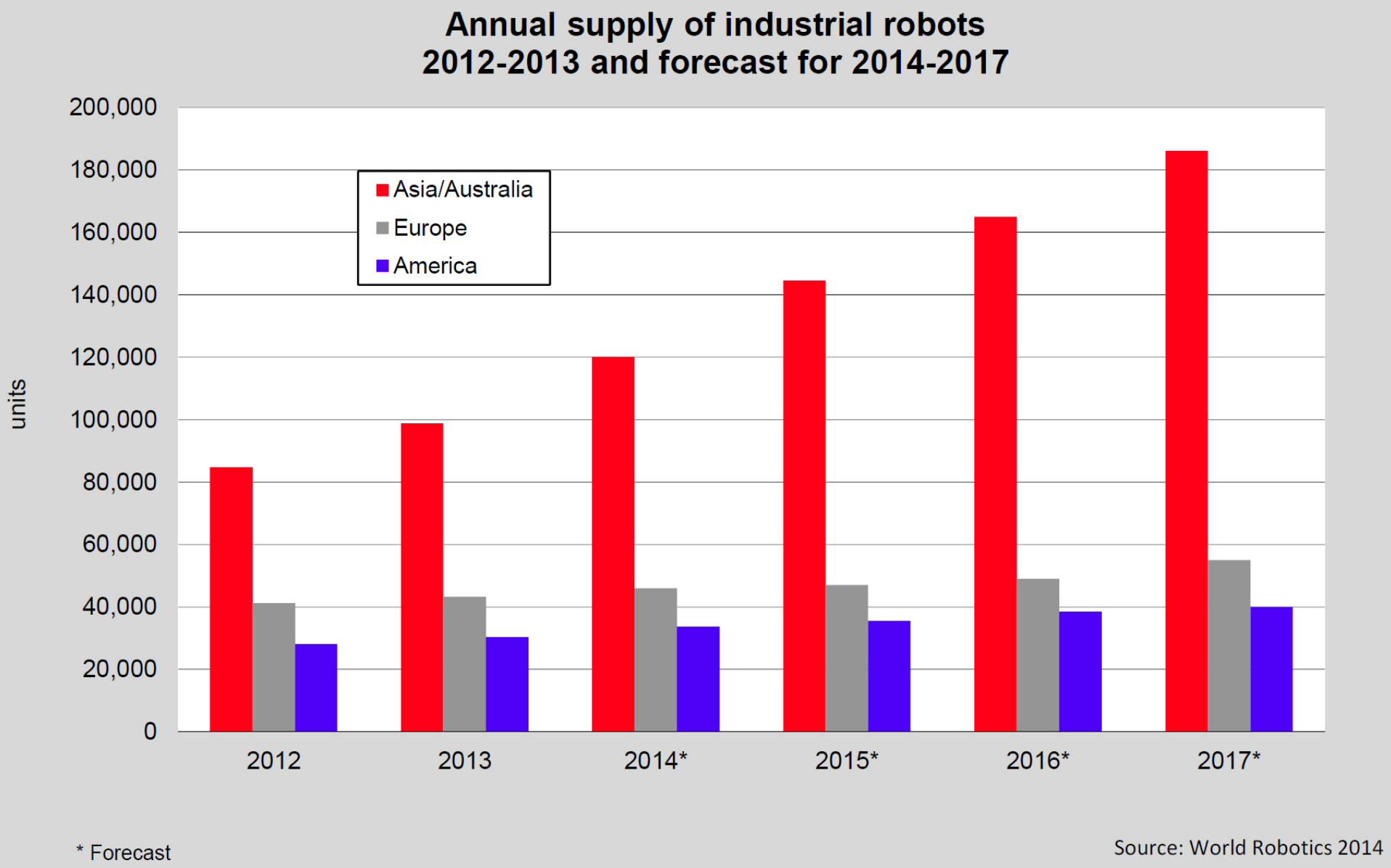
World Statistics

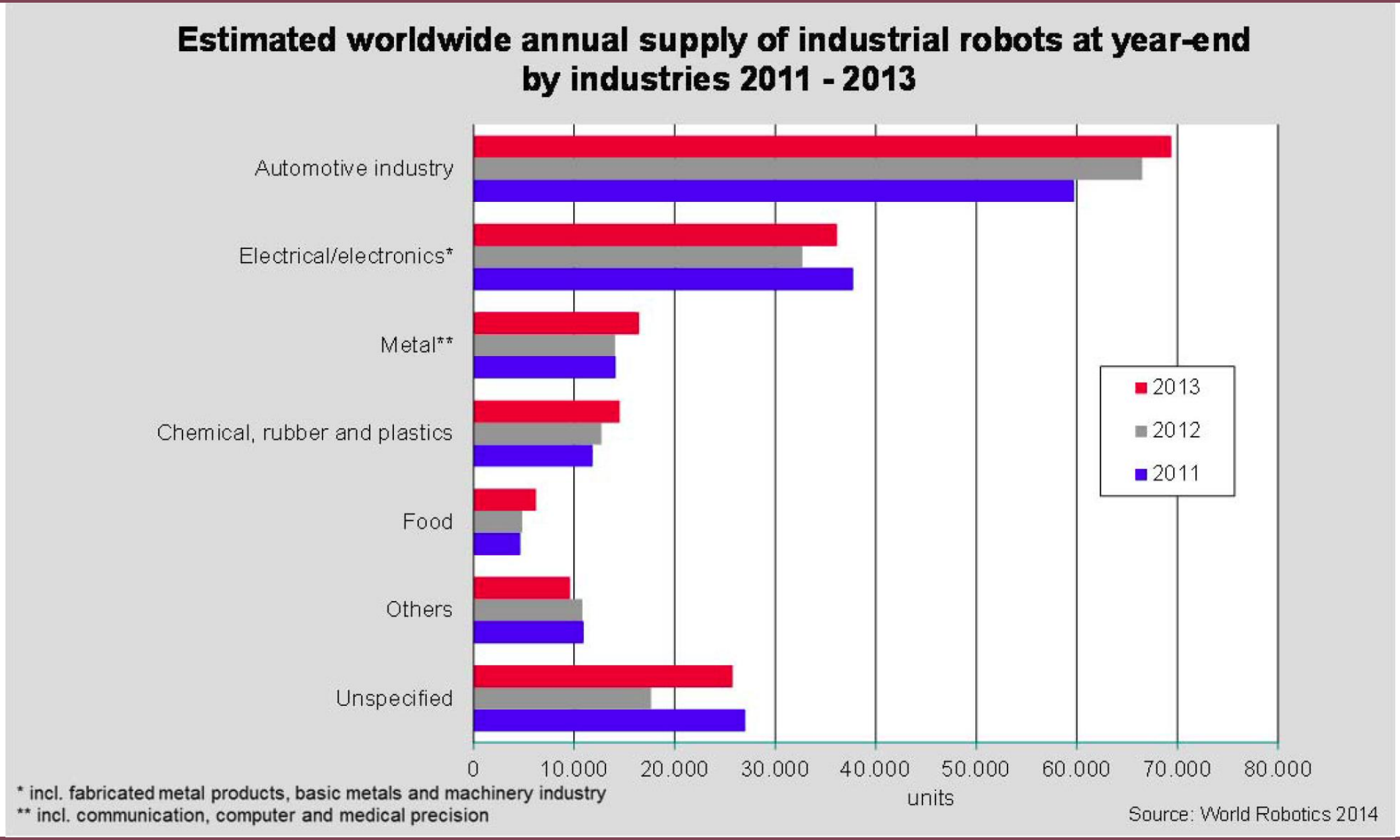
Average service life of industrial robot: about 12 years … may increase to 15 in a few years from now.

Robot density based on total number of persons employed

- 347 robots in operation per 10,000 workers in Korea
- 339 in Japan
- 261 in Germany
- 149 in Italy

Average cost of a 6-axis industrial robot, including control unit and development software: 20,000÷60,000 €, depending on size and applications


Annual supply of industrial robots
2012-2013 and forecast for 2014-2017
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
units
Asia/Australia
Europe
America
2012
2013
2014*
2015*
2016*
2017*
* Forecast
Source: World Robotics 2014


Estimated worldwide annual supply of industrial robots at year-end by industries 2011 - 2013
Automotive industry
Electrical/electronics*
Metal**
Chemical, rubber and plastics
Food
Others
Unspecified
2013
2012
2011
0
10.000
20.000
30.000
40.000
50.000
60.000
70.000
80.000
units
* incl. fabricated metal products, basic metals and machinery industry
** incl. communication, computer and medical precision
Source: World Robotics 2014

Industrial Robot Arms

SECTION 4

Market Research Reports

World's Top 10 Industrial Robot Manufacturers

Company	Head Quarter	About
ABB	Zurich, Switzerland	**ABB** (ASEA Brown Boveri) is a Swiss-Swedish MNC based out in Zurich, Switzerland. ABB is a leading supplier of industrial robots and robot software, equipment and complete application solutions.
YASKAWA	Kitakyushu, Japan	**The Yaskawa Electric Corporation** is a Japanese manufacturer headquartered in (Kurosakishiroishi, Yahatanishi-ku, Kitakyushu) Japan. The company manufacturers servos, motion controllers, AC motor drives, switches and industrial robots.
KUKA	Bavaria, Germany	**KUKA** (Keller und Knappich Augsburg) is a German manufacturer headquartered in Bavaria, Germany. The company manufactures industrial robots and solutions for factory automation.
FANUC	Yamanashi Prefecture, Japan	**FANUC Corporation** is headquartered in (Oshino-mura, Minamitsuru-gun, Yamanashi Prefecture) Japan. The company provides automation products and services such as robotics and wireless systems.
Kawasaki	Tokyo, Japan	**Kawasaki Heavy Industries Ltd.** (KHI) is a Japanese multinational corporation based in Tokyo, Japan. The company is a leading manufacturer of motorcycles, heavy equipment, aerospace and defense equipment, rolling stock and ships.

Market Research Reports

World's Top 10 Industrial Robot Manufacturers

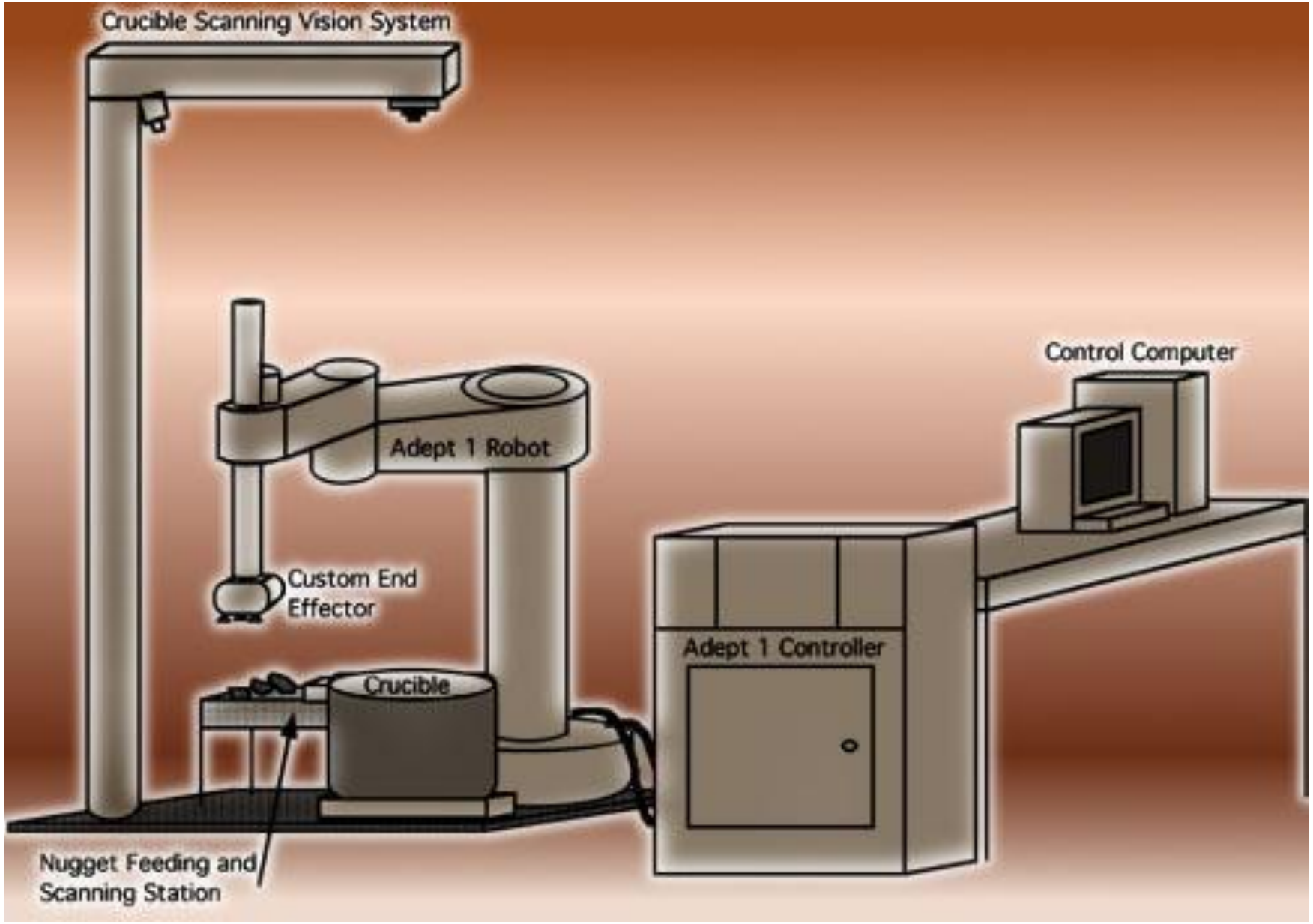
Company	Head Quarter	About
EPSON	Tokyo, Japan	**Seiko Epson Corporation or EPSON**, is a Japanese electronics company based in Tokyo, Japan. Company is a leading manufacturers of computer printers, and information and imaging related equipment. EPSON manufactures and design robots under EPSON Robots department.
STÄUBLI	Pfäffikon, Switzerland	**Stäubli** is a Swiss mechatronics company, headquartered in Pfäffikon, Switzerland. The company manufactures textile machinery, connectors and robotics products.
NACHI NACHI-FUJIKOSHI CORP.	Toyama, Japan	**Nachi-Fujikoshi Corp.** or Nachi is a Japanese corporation headquartered in Toyama, Japan. The company manufactures industrial robots, machining tools and systems and machine components.
COMAU	Turin, Italy	**Comau** is a leading company in the industrial automation field headquartered in Turin, Italy. Company is a subsidiary of automaker Fiat Chrysler Automobiles.
omron adept	California, U.S.	**Omron Adept Technology, Inc.** is a multinational corporation with headquarters in Pleasanton, California. The company provides solution (product and services) for industrial automation and robotics, including software and vision guidance.

SCARA Robot

AdeptOne XL Robot

- SCARA structure
- Direct drive motors
- Maximum reach of 800 mm
- Repeatability of 0.025 mm horizontally and 0.038 mm vertically
- Maximum speed of 1200 mm/s for the prismatic joint and 650÷3300 deg/s for the three revolute joints
- Maximum payload of 12 kg
- Typical industrial application: Small-parts material handling, Assembly, Packaging

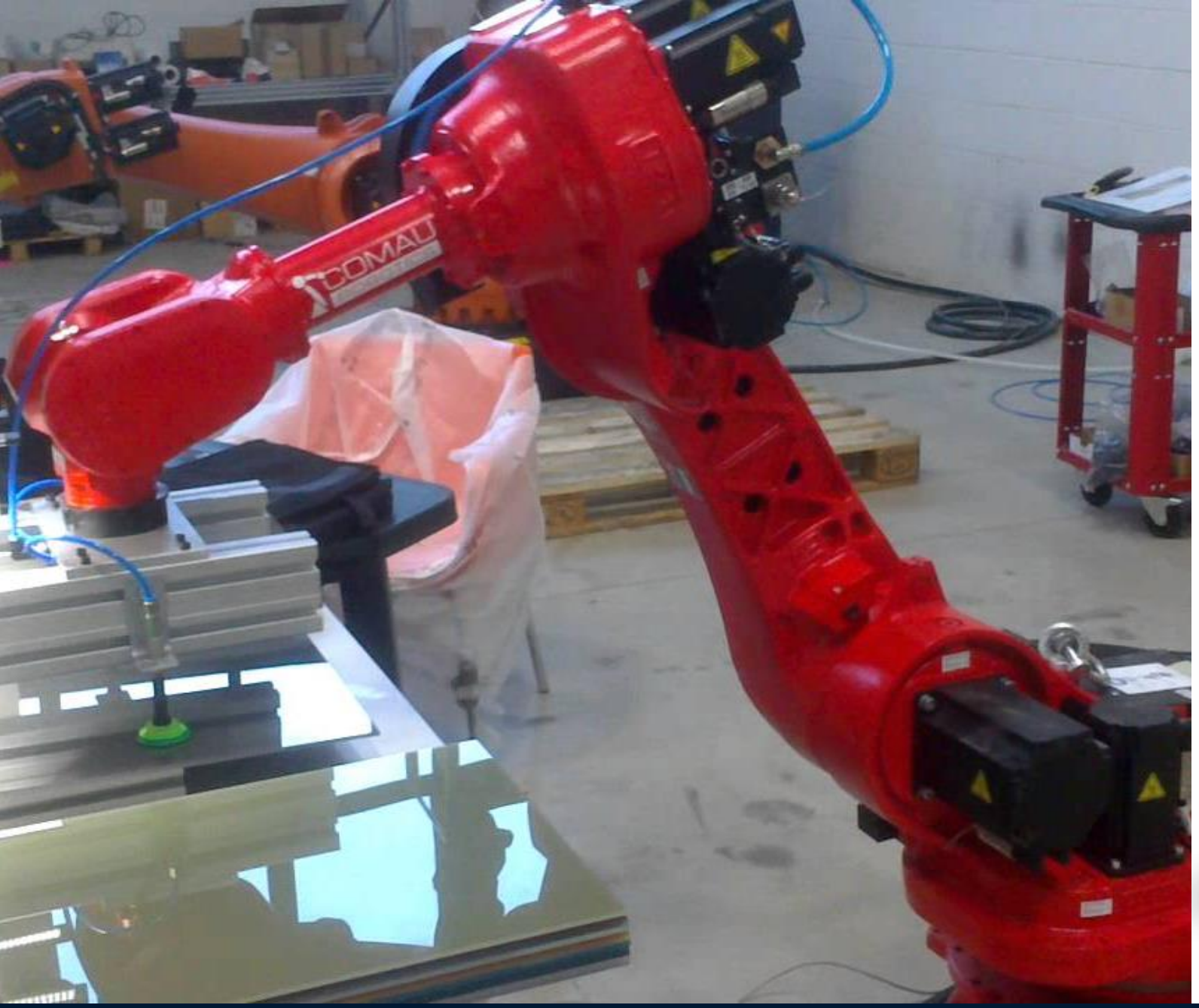
adept


Crucible Scanning Vision System
Control Computer
Adept 1 Robot
Custom End Effector
Adept 1 Controller
Crucible
Nugget Feeding and Scanning Station

Anthropomorphic Robot

COMAU Smart NS Robot

- Six-joint anthropomorphic structure with spherical wrist
- Horizontal outreach of 1650÷1850 mm
- Repeatibility of 0.05 mm
- Maximum speeds of 155÷170 deg/s for the inner three joints and 350÷550 deg/s for the outer three joints
- Maximum payload of 16 kg
- Floor and ceiling mounting positions
- Typical industrial applications: Arc welding, Light handling, Assembly, Technological processes

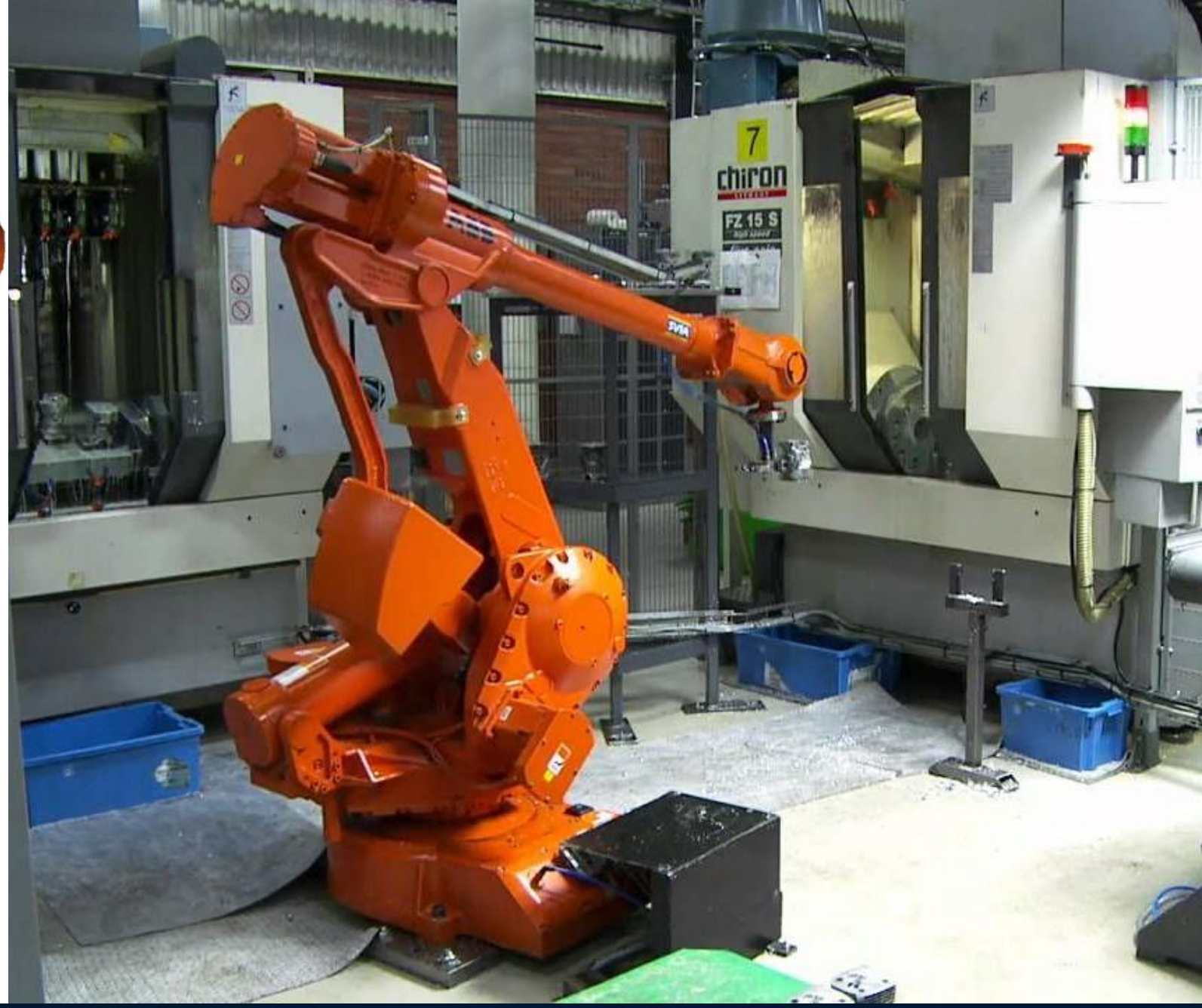

COMAU

Anthropomorphic Robot With Parallelogram

ABB IRB 4400 Robot

- Six-joint anthropomorphic structure with closed chain of parallelogram type between shoulder and elbow joints
- Outreach of 1960÷2550 mm
- Repeatability of 0.07÷0.1 mm
- Maximum end-effector speed of 2200 mm/s
- Floor or shelf-mounting
- Typical industrial applications: Material handling, Machine tending, Grinding, Gluing, Casting, Die spraying, Assembly

ABB
ABB
ABB


7
chiron
FZ 15 S

Gantry Robot

KUKA KR 60 Jet Robot

- Five-axis structure mounted on sliding track with gantry-type installation
- Linear unit with a stroke of 0.4÷20 m
- Maximum speed of 3200 mm/s
- Payload of 60 kg
- Outreach of 820 mm
- Repeatability of 0.15 mm
- Maximum speeds of 120 deg/s and 166 deg/s for the first two joints and 260÷322 deg/s for the outer three joints
- Typical industrial applications: Machine tending, Arc welding, Deburring, Coating, Sealing, Plasma and waterjet cutting

Parallel Robot

ABB IRB 340 FlexPicker Robot

- Parallel geometry with four axes
- Reduced weight and floor mounting (robot can transport 150 objects a minute cycle time of just 0.4 s)
- Record speeds of 10 m/s and accelerations of 100 m/s2
- Payload of 1 kg
- Repeatability of 0.1 mm
- Clean aluminum version employed for packaging
  - Food industry
  - Pharmaceutical industry

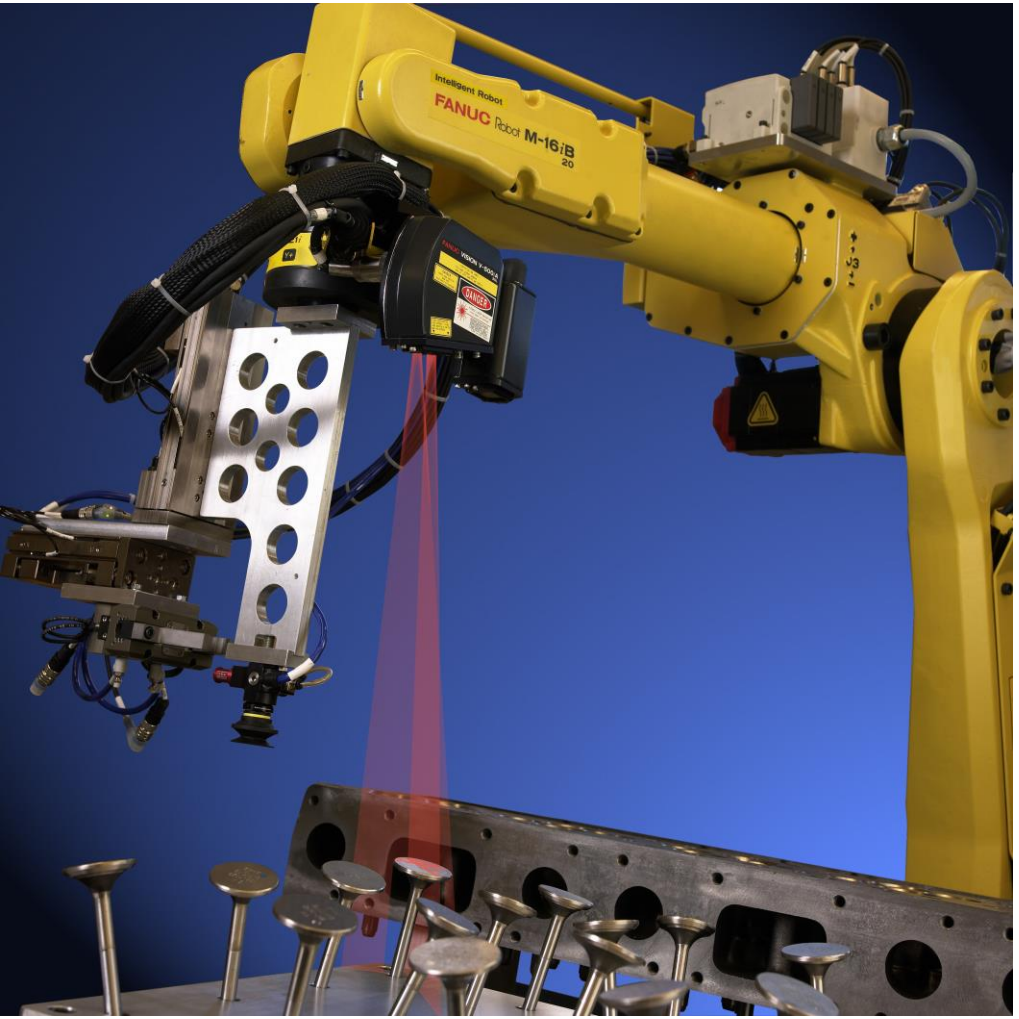
ABB

Delta4
FlexPicker™
ABB

Robot With Vision and Force Sensors

Fanuc M-16iB Robot

- Anthropomorphic structure with spherical wrist
- Horizontal outreach 1667÷1885 mm
- Repeatability of 0.1 mm
- Maximum speeds from 165 to 175 deg/s for the inner three joints and 340 to 520 deg/s for the outer three joints
- Payload of 10÷20 kg Integrated sensors in control unit: servoing system based on 3D vision and six-axis force sensor
- Typical industrial applications: Handling arbitrarily located objects, Deburring, Sealing, Waterjet cutting

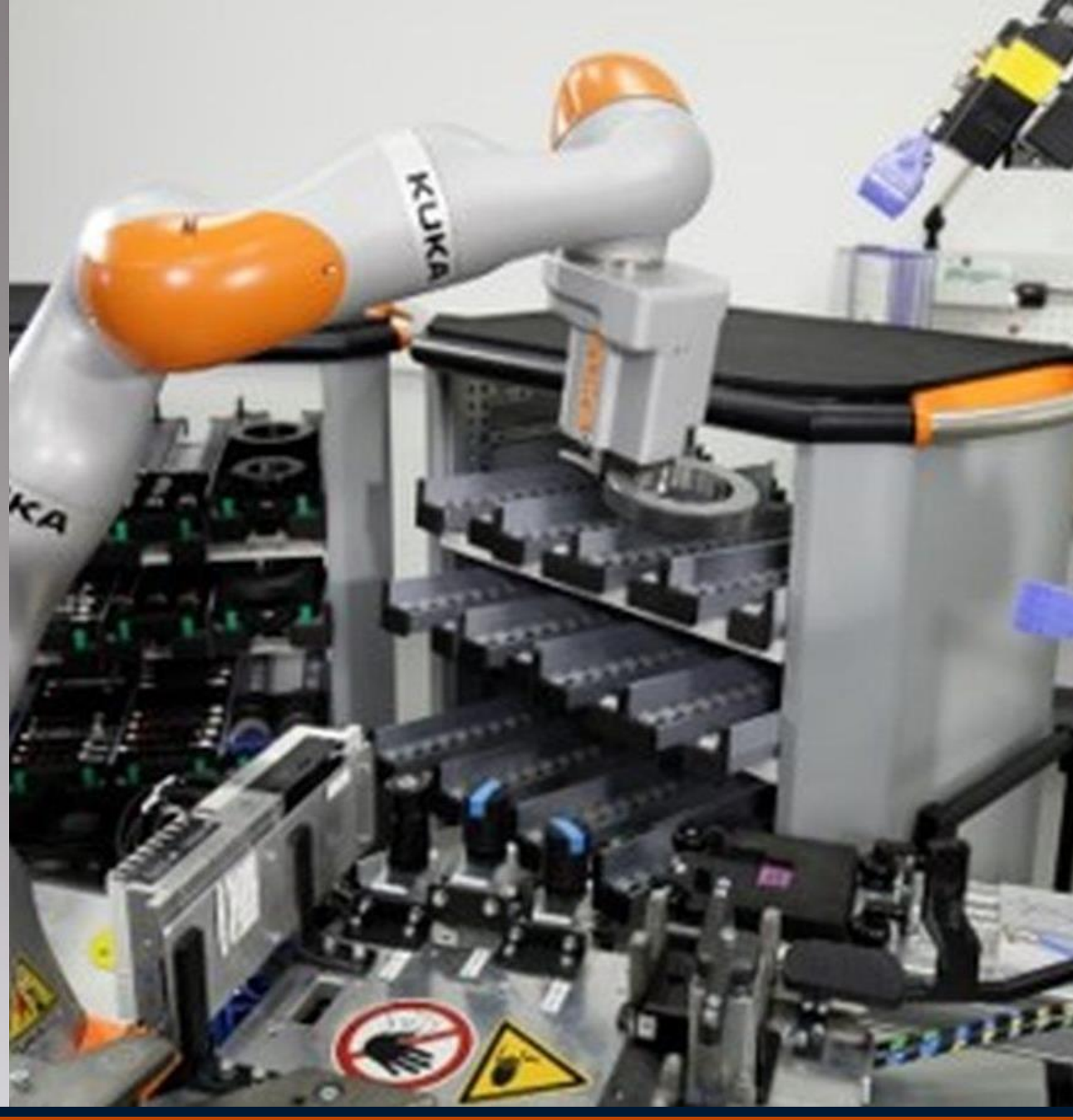

Intelligent Robot
FANUC Robot M-16iB
20

Lightweight Robot

KUKA LWR Robot

- Seven-axis structure as outcome of technology transfer from DLR (German Aerospace Agency) to KUKA
- Adoption of lightweight materials and joint torque sensors
- Horizontal outreach of 868 mm
- Joint speeds of 110÷210 deg/s
- Payload of 7÷14 kg in the face of weight of structure of just 15 kg
- Kinematic redundancy (reconfigurable into more dexterous postures for execution of given tasks)
- Good performance for interaction with the environment ensuring inherent safety in case of contact with human beings.

KUKA


KUKA

Multi-fingered Hands

BarrettHand

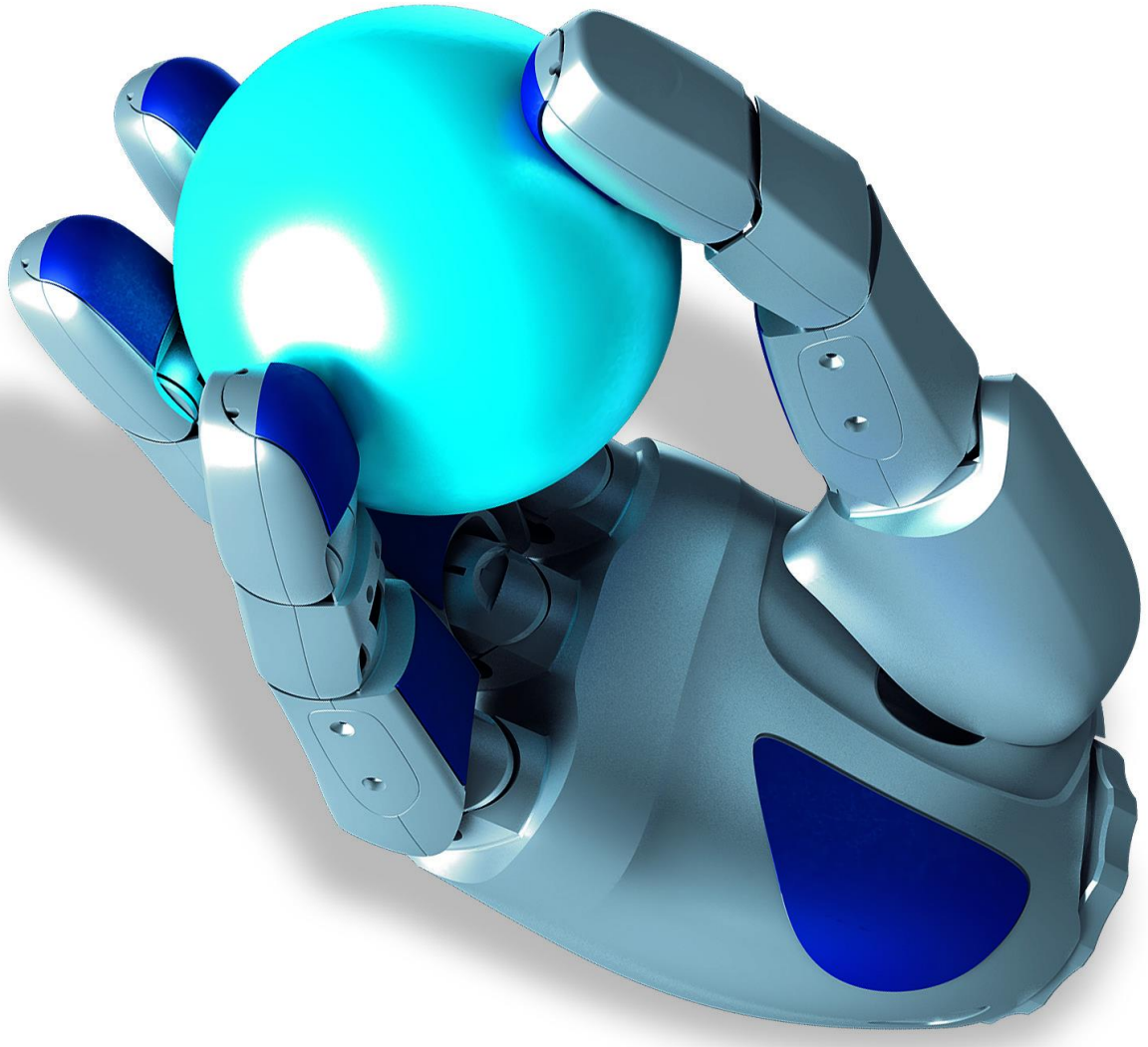
- Fixed finger and two mobile fingers around base of palm
- Manipulation of objects of different dimension, shape and orientation

F1
F2
F3

Multi-fingered Hands

SCHUNK Antropomorphic Hand

- Outcome of technology transfer from DLR and Harbin Institute of Technology (China) to SCHUNK
- Three independent aligned fingers and opposing finger analogous to human thumb
- Finger joints endowed with magnetic angular sensors and torque sensors
- Good dexterity approaching human hand's



Humanoid Robot Manipulator

Justin Humanoid Robot Manipulator

- Three-joint torso with anthropomorphic structure
- Two seven-axis arms (LWR technology)
- Sensorized head
- Bimanual manipulation task

Humanoid Robot Manipulator

Justin Humanoid Robot Manipulator

Videos

- Coffee making with Justin robot (courtesy of DLR)
- Catching flying balls and preparing coffee: Humanoid Rollin'Justin performs dynamic and sensitive tasks
- Robot catching balls
- Agile & Rollin' Justin playing ball

Field Robots

SECTION 5

Field and Service Robots

- Field robots are needed whenever human operators are not available or are not safe
- Service robots are aimed at improving quality of life

Advanced Robotics

Advanced robotics ≡ Science studying robots with marked characteristics of *autonomy* operating in scarcely structured or *unstructured environments* whose geometrical or physical characteristics would not be known a priori

- Still in its youth: realization of prototypes only, because associated technology is not yet mature

Field Robots

- Need for automata whenever human operators are not available
- Safety motivation in hostile environments

Service Robots

- Opportunity of developing products for potentially wide markets aimed at improving quality of life

Videos

The most awesome robots

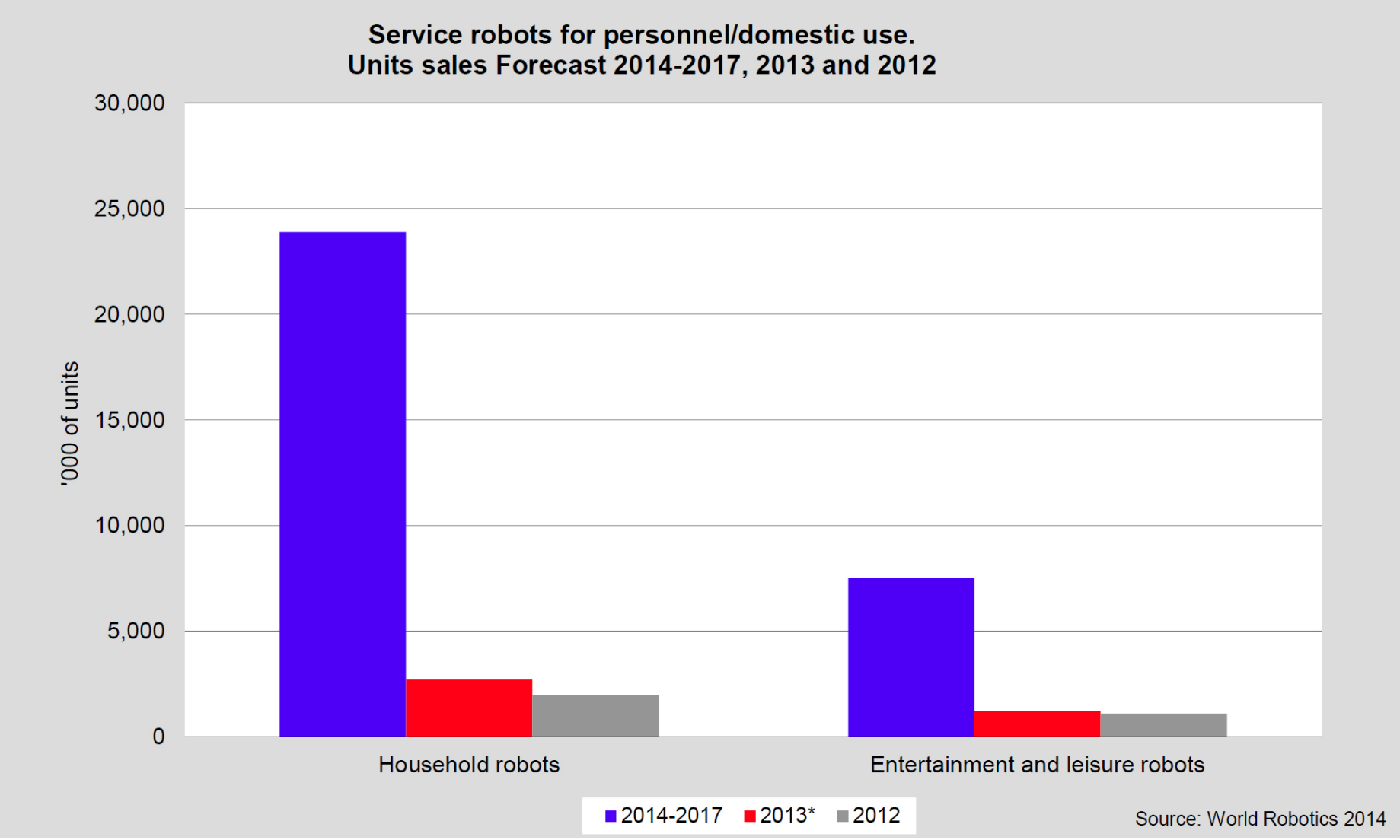
Robots for Non-industrial Applications

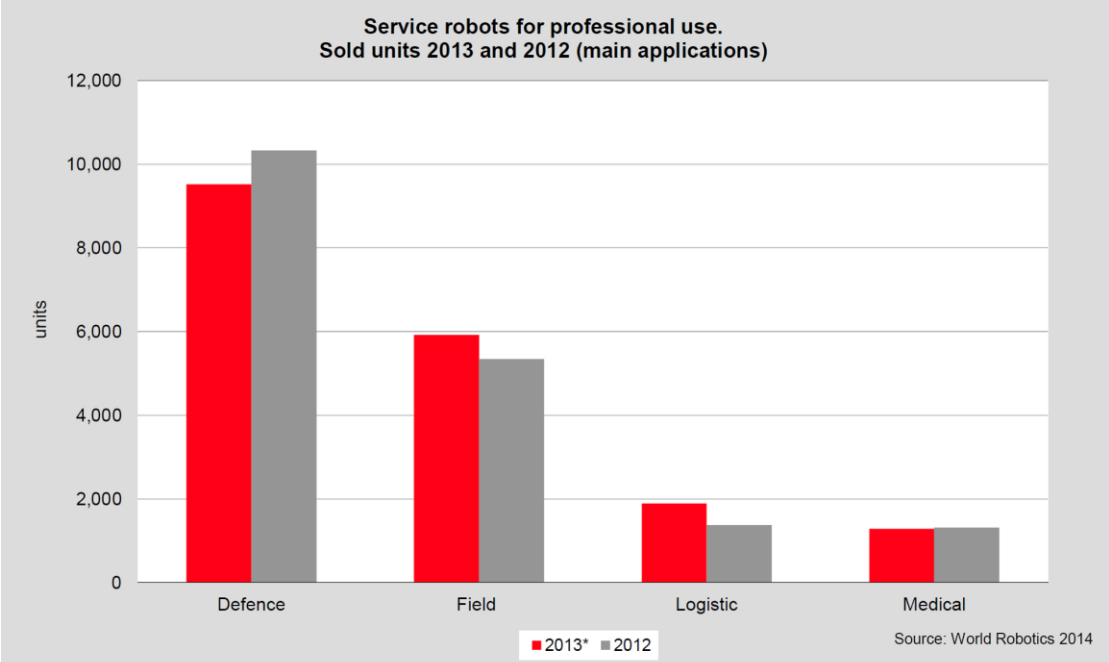
Data up to 12/2013 (Annual report by International Federation of Robotics) Service robots for professional use

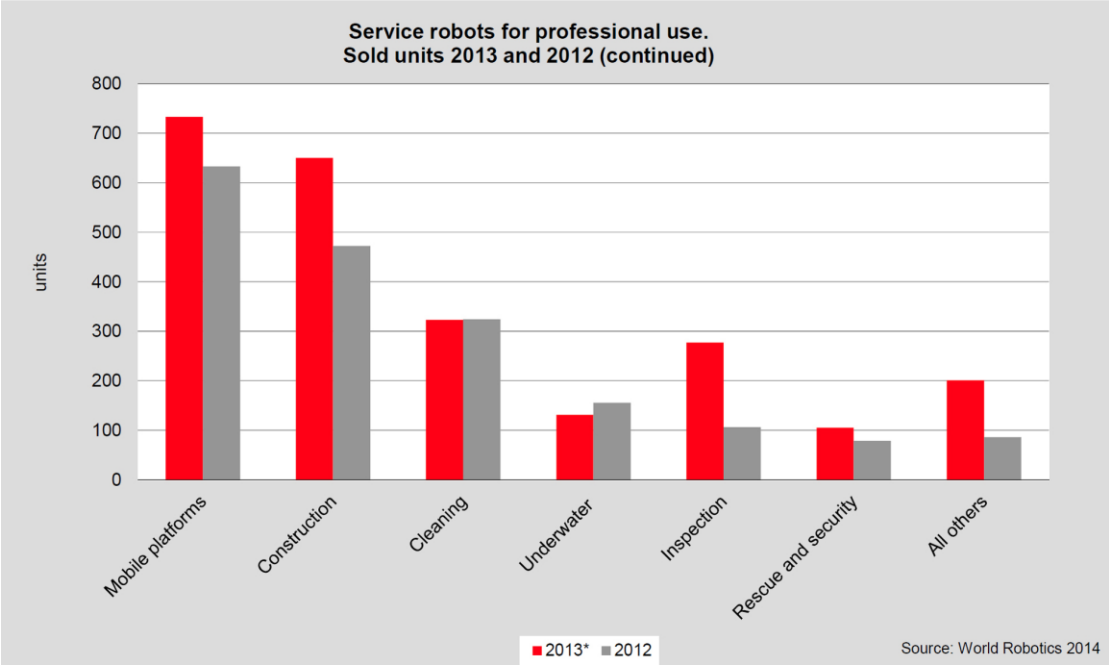
- Military applications and hostile environments
- 21.000 new installations in 2013

Service robots for personal/domestic use

- 2,700,000 robots for domestic applications
- 1,200,000 robots for entertainment


Service robots for personnel/domestic use.
Units sales Forecast 2014-2017, 2013 and 2012
30,000
25,000
20,000
15,000
10,000
5,000
0
'000 of units
Household robots
Entertainment and leisure robots
2014-2017
2013*
2012
Source: World Robotics 2014


Service robots for professional use.
Sold units 2013 and 2012 (main applications)
units
12,000
10,000
8,000
6,000
4,000
2,000
0
Defence
Field
Logistic
Medical
2013*
2012
Source: World Robotics 2014


Service robots for professional use.
Sold units 2013 and 2012 (continued)
units
800
700
600
500
400
300
200
100
0
Mobile platforms
Construction
Cleaning
Underwater
Inspection
Rescue and security
All others
2013*
2012
Source: World Robotics 2014

Field Robots

Exploration (reporting data on environment to remote operator using suitable onboard sensors)

- Volcanos
- Aerial
- Underwater
- Space

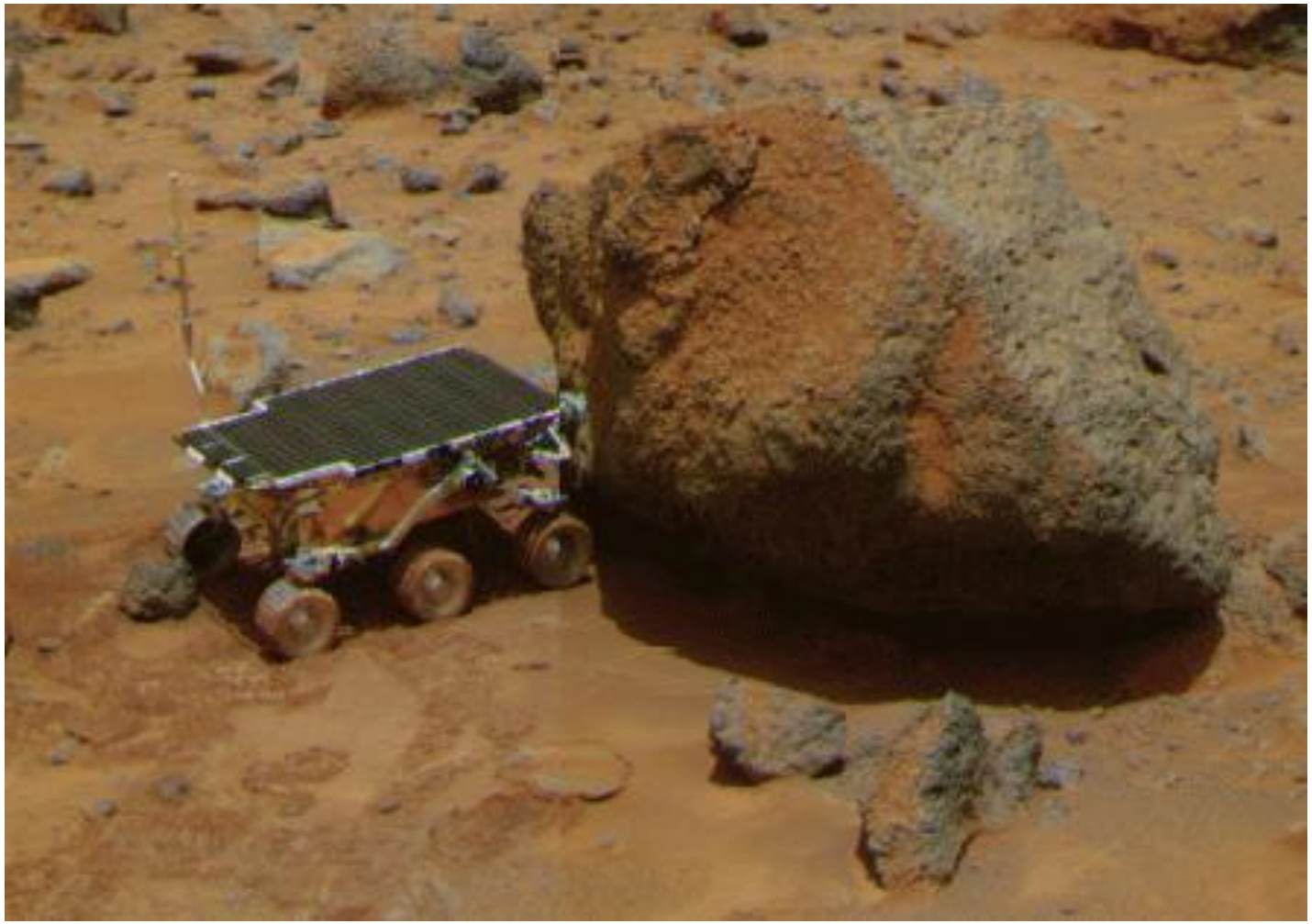
Rescue intervention (deploying robots in areas where humans could not survive or be exposed to unsustainable risks; human teams may cooperate with robot teams)

- Areas contaminated by poisonous gas or radiation
- Scenarios caused by disasters (criminal attacks, collapses, earthquakes)

Videos

NASA celebrates Mars rovers' 10-year mark
Boston Dynamics Big Dog
DARPA Grand Challenge – 2005 Driverless Car Competition

The Sojourner rover was deployed by the Pathfinder lander and explored 250 square meters of Martian soil in 1997 (courtesy of NASA)



The unmanned car Stanley autonomously completed a path of 132 miles in the record time of 6 h and 53 min (courtesy of DARPA)

Service Robots

SECTION 6

Rhino, employing the synchro-drive mobile base B21 by Real World Interface, was one of the first robots for museum guided tours (courtesy of Deutsches Museum Bonn)

The Cycab is an electrically-driven vehicle for autonomous transportation in urban environments (courtesy of INRIA)

The vacuum robot Roomba, employing a differential-drive kinematics, autonomously sweeps and cleans floors (courtesy of I-Robot Corp)

More Service Personal Robots

Videos

- Roomba cat swats dog pit bull sharky
- Jibo: The world's first family robot
- A first drive: Google self-driving car project

Service Professional Robots

Videos

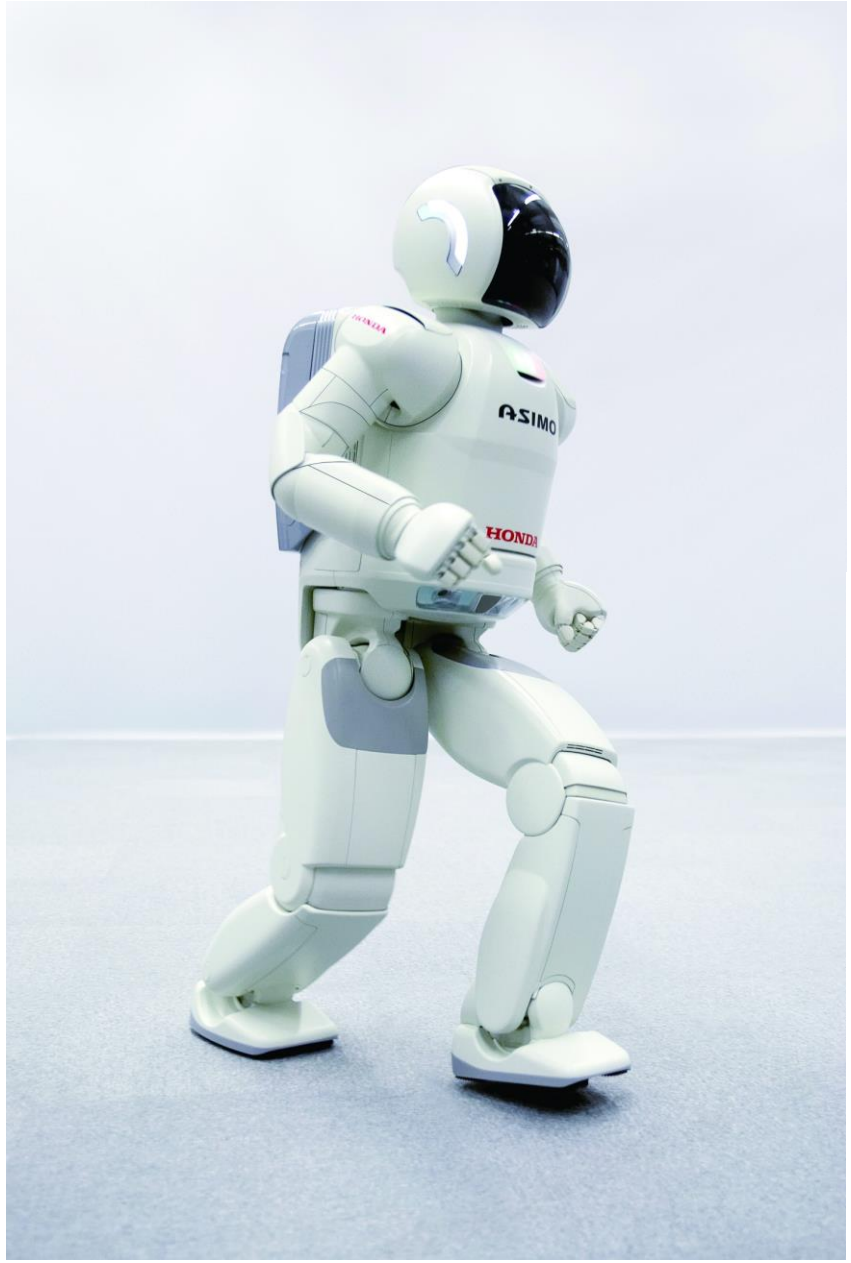
- Robotic surgery demonstration using da Vinci surgical system
- POWER KNEE™ by Össur – Allison Brown's story
- Cyberdyne power suit

The da Vinci robotic system for minimally invasive surgery (courtesy of Intuitive Surgical Inc)

Companion Robots

SECTION 7

The AIBO dog had been the most widely diffused entertainment robot in the recent years (courtesy of Sony Corp)



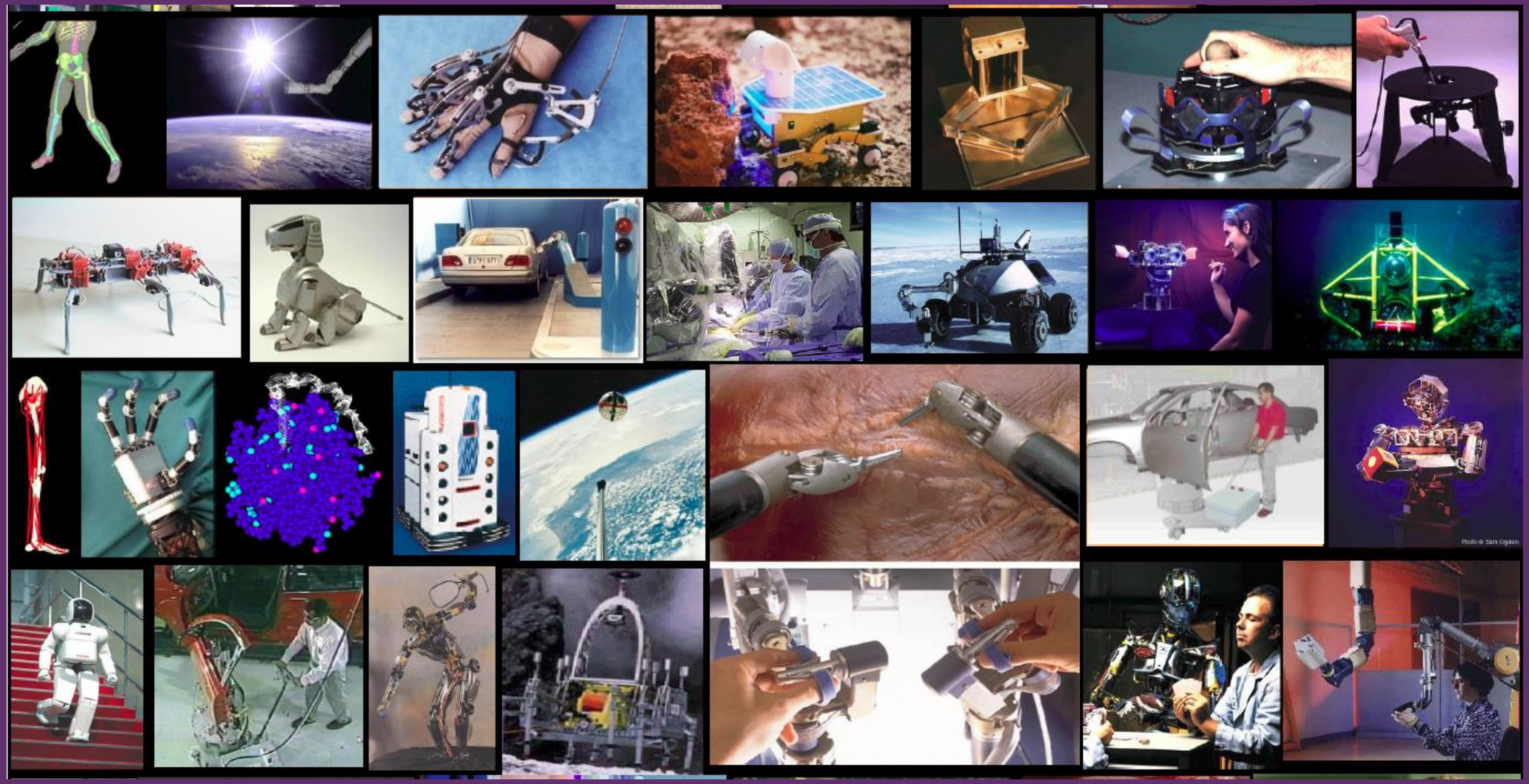
The **Asimo humanoid,** launched in 1996, has been endowed with more natural locomotion and human-robot interaction skills (courtesy of Honda Motor Company Ltd)

More Companion Robots

Videos

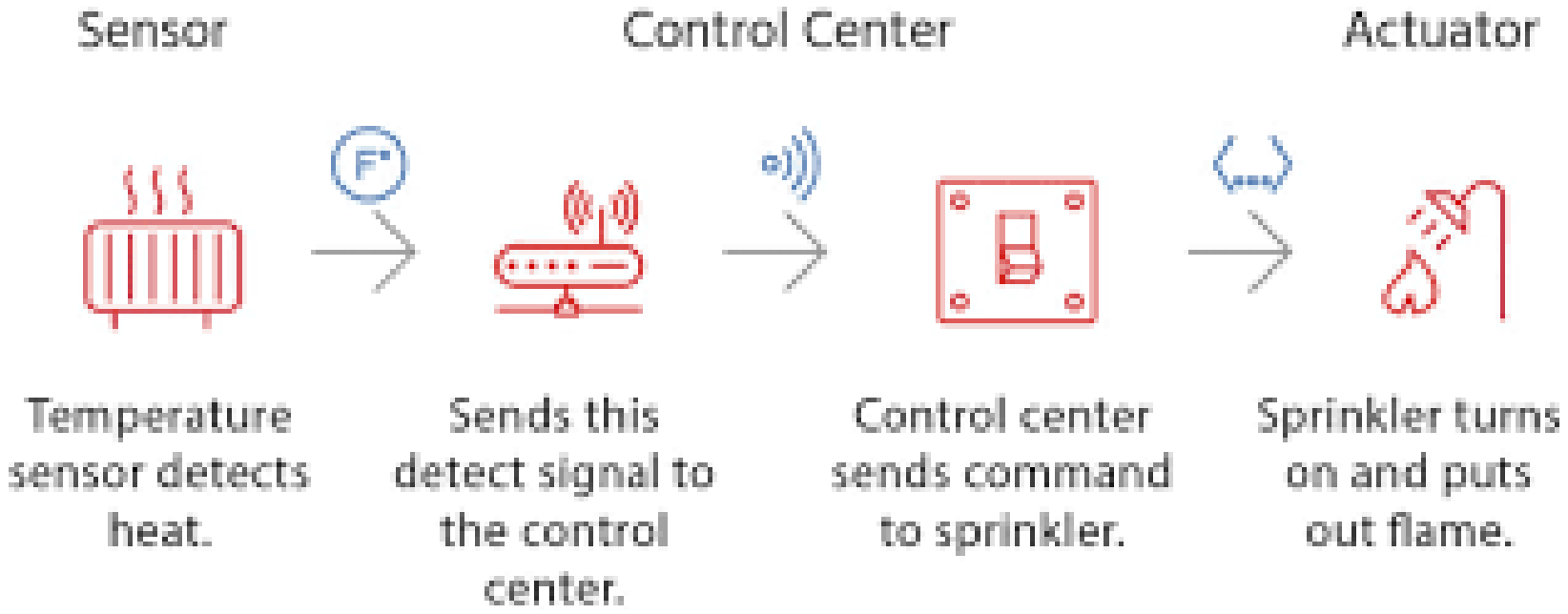
- JediBot: Robot-human sword fighting
- ASIMO robot serving a glass of water
- ASIMO has found a new home
- Robotic seals help heal Japan's elderly tsunami victims
- Robot therapy engages children with autism

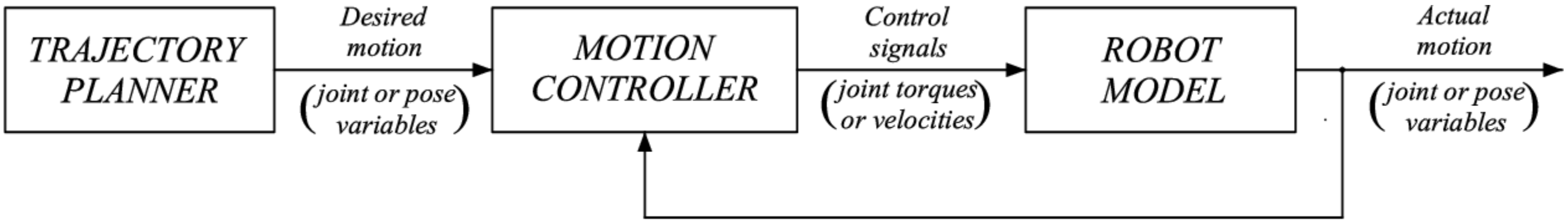
Multiple applications of robots

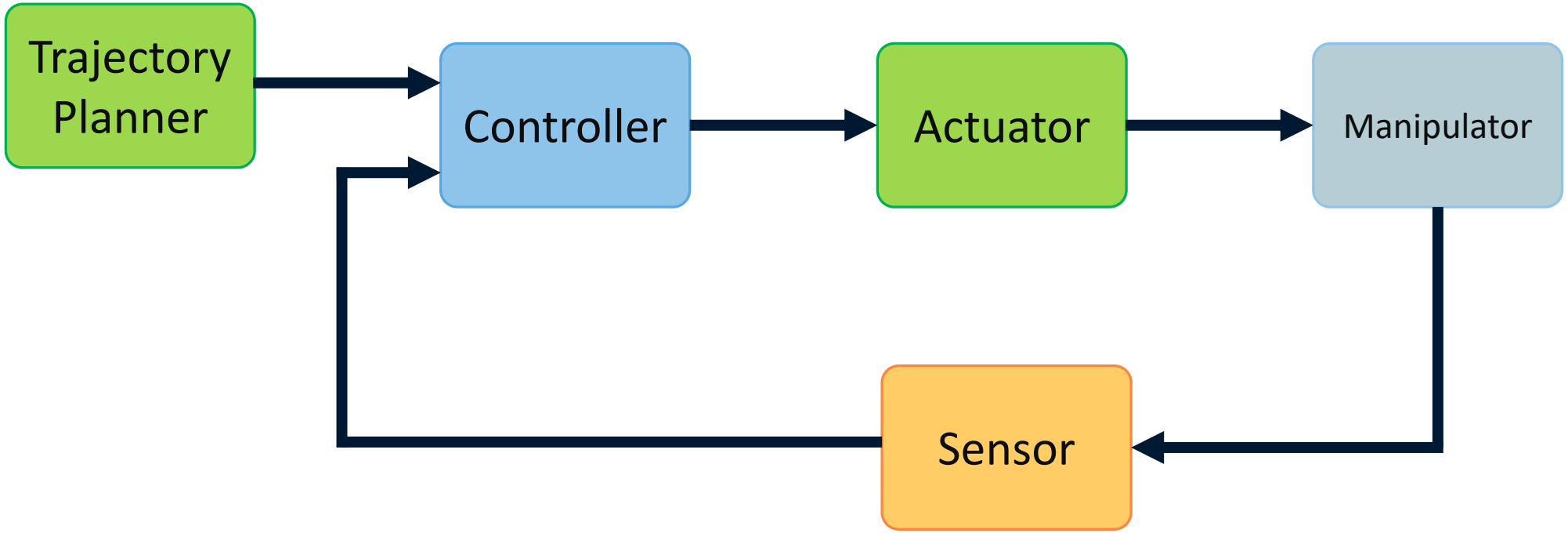


Modeling, Planning, and Control

SECTION 8

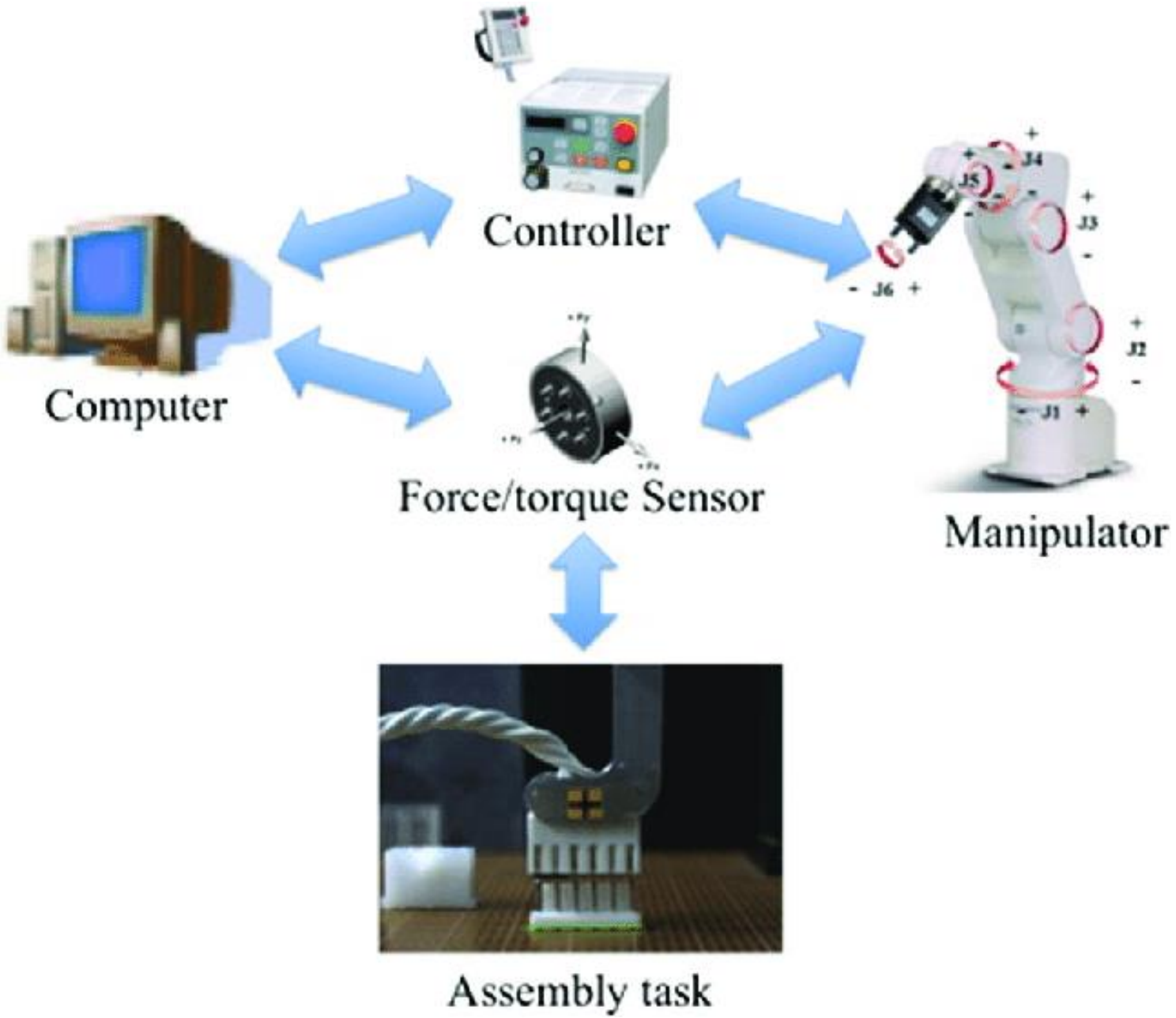

Sensor
Control Center
Actuator
Temperature sensor detects heat.
Sends this detect signal to the control center.
Control center sends command to sprinkler.
Sprinkler turns on and puts out flame.


TRAJECTORY PLANNER
Desired motion
(joint or pose variables)
MOTION CONTROLLER
Control signals
(joint torques or velocities)
ROBOT MODEL
Actual motion
(joint or pose variables)


Trajectory Planner
Controller
Actuator
Manipulator
Sensor

Robot Modelling, Planning and Control

- The correct execution of such motion is entrusted to the **control system** which should provide the robot's actuators with the commands consistent with the desired motion.
- Motion control demands an accurate analysis of the characteristics of the mechanical structure, **actuators**, and **sensors**.
- The goal of such analysis is the derivation of the mathematical models describing the input/output relationship characterizing the robot components.
- Modelling a **robot manipulator** is therefore a necessary premise to finding motion control strategies.
- Significant topics in the study of modelling, planning and control of robots which constitute the subject of subsequent chapters are illustrated below.


Controller
Computer
Force/torque Sensor
Manipulator
Assembly task

Modelling

- Kinematics: Kinematic analysis of the mechanical structure of a robot concerns the description of the motion with respect to a fixed reference **Cartesian** frame by ignoring the forces and moments that cause motion of the structure.
- With reference to a robot manipulator, kinematics describes the analytical relationship between the **joint positions** and the **end-effector position** and **orientation**.

Modelling

- Dynamic Kinematics: Differential kinematics describes the analytical relationship between the joint **motion** and the end-effector **motion** in terms of **velocities**, through the manipulator **Jacobian**.

Unit 1: Introduction (1-Week)

- Chapter 1 is dedicated to the introduction of Robotics
- Appendix A provides a useful brush-up on linear algebra.
- Unit 1 introduces all aspects of robotics and prepares students in python and mathematics to deal with problem in this course.

(2, 3, 7, AB)

Unit 2: Kinematics (3-weeks)

- Unit 2 covers the Kinematics Modeling and Planning.
- Chapter 2 is dedicated to the study of kinematics.
- Chapter 3 is dedicated to the study of differential kinematics and statics, whereas
- Chapter 4 is dedicated to **trajectory planning** for robot manipulators.

Unit 2: Kinematics

The availability of the **dynamic model** is very useful for mechanical design of the structure, choice of actuators, determination of control strategies, and computer simulation of manipulator motion.

- Chapter 7 is dedicated to the study of dynamics, whereas
- Appendix B recalls some fundamentals on rigid body mechanics.

Unit 2: Kinematics

- The goal of **trajectory planning** is to generate the timing laws for the relevant variables (joint or end-effector) starting from a concise description of the desired motion.

Unit 2: Kinematics

- With reference to the tasks assigned to a manipulator, the issue is whether to specify the motion at the joints or directly at the end-effector.
- In material handling tasks, it is sufficient to assign only the pick-up and release locations of an object, whereas, in machining tasks, the end-effector has to follow a desired trajectory.

(4, 11, 12, E)

Unit 2: Kinematics

- The motion planning problem for a mobile robot concerns the generation of trajectories to take the vehicle from a given initial configuration to a desired final configuration. Such a problem is more complex than that of robot manipulators, since trajectories have to be generated in respect of the kinematic constraints imposed by the wheels.

Unit 2: Kinematics

- Whenever obstacles are present in a mobile robot's workspace, the planned motions must be safe, so as to avoid collisions.
- Such a problem, known as **motion planning**, can be formulated in an effective fashion for both robot manipulators and mobile robots utilizing the configuration space concept.
- The solution techniques are essentially of algorithmic nature and include exact, **probabilistic** and **heuristic** methods.

Unit 3: Sensor and Vision (1-2 weeks)

- Unit 3 covers sensor, actuator, image processing and low-level vision.
- Chapter 5 covers sensor and actuator
- Chapter 10 covers visual servoing
- We may spend 1-2 weeks in this unit.

Unit 3: Sensor and Actuators

- Realization of the motion specified by the control law requires the employment of actuators and sensors. The functional characteristics of the most commonly used actuators and sensors for robots are described in Chap. 5.

(5, 6, 8, 9, 10)

Unit 4: Control (2-3 Weeks)

- Unit 4 covers control architecture, control design and mobile robot control.
- Week 7 covers control architecture
  - Chapter 6: control architecture
  - Chapter 7: dynamics (optional)
  - Chapter 9: force control (optional)

Unit 4: Control (2-3 Weeks)

- Week 2 covers control design
  - Chapter 8 Motion Control
  - Chapter 11 (optional), which exploit the specific differential structure of the mobile robots' kinematic models.
  - Chapter 12 (optional) is dedicated to **motion planning** problem, while
  - Appendix E provides some basic concepts on graph search algorithms.

Unit 4: Control

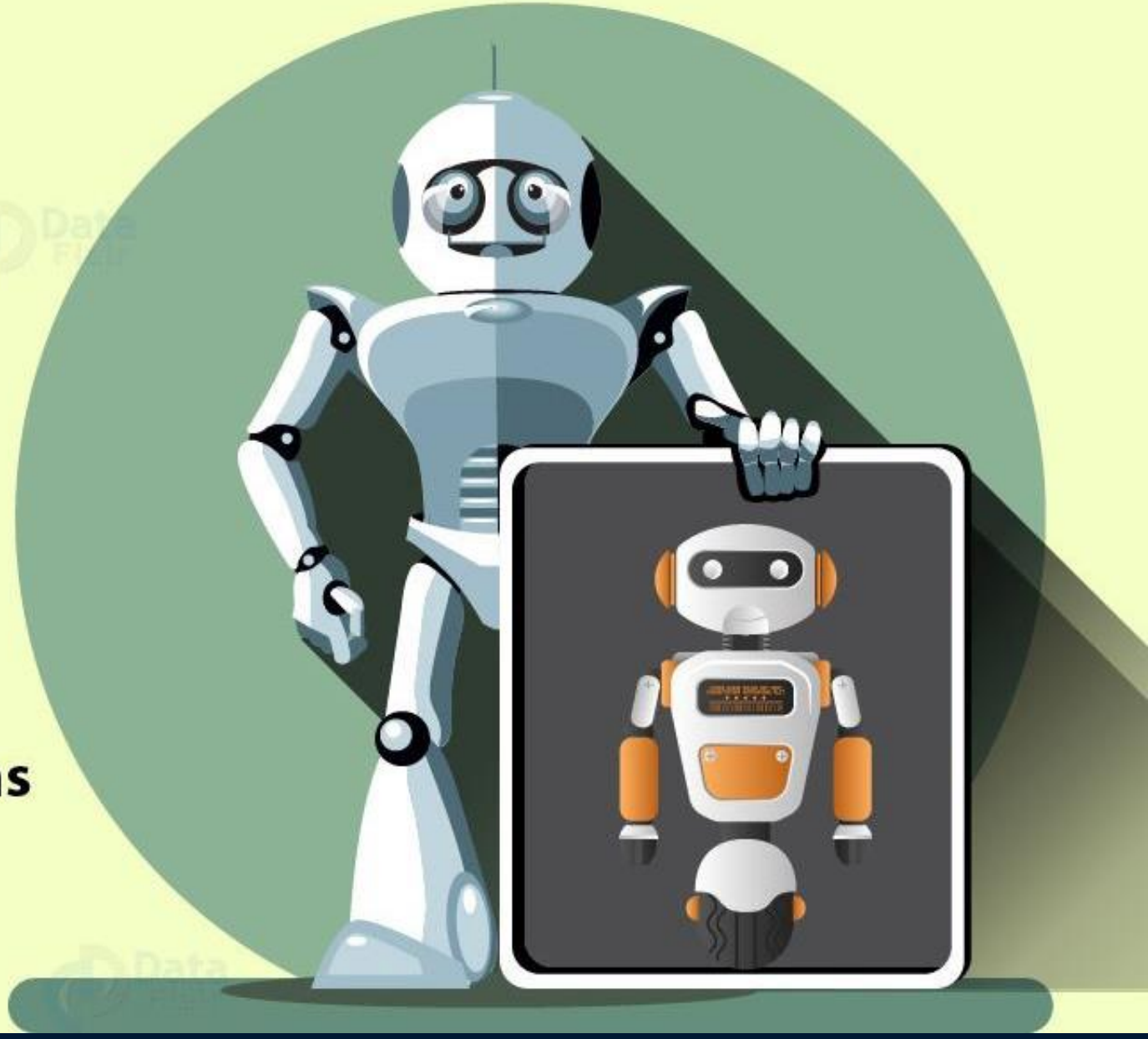
- Chapter 6 is concerned with the hardware/software architecture of a robot's control system which is in charge of implementation of control laws as well as of interface with the operator.

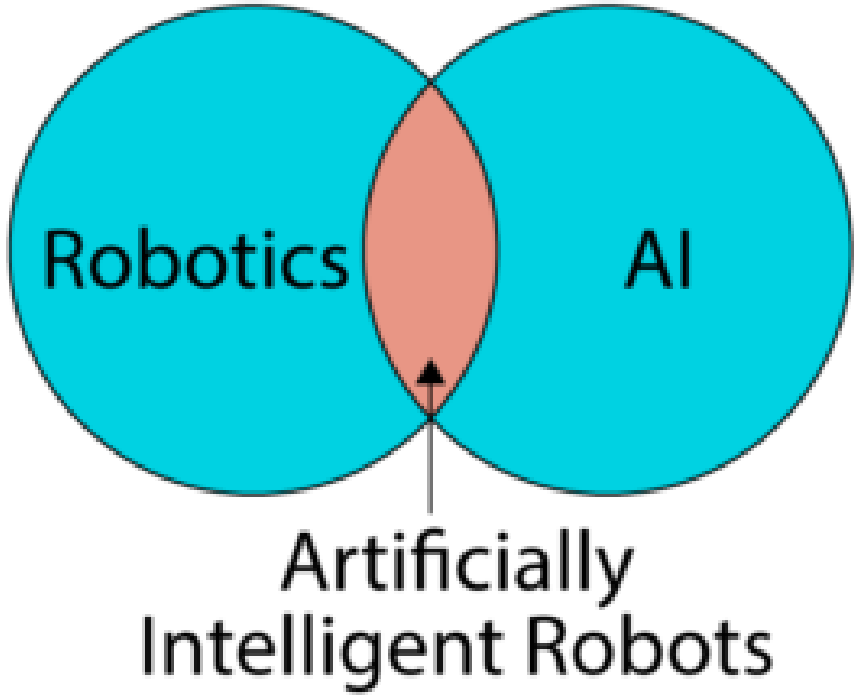
Unit 4: Control

- Chapter 8 is dedicated to the presentation of motion control techniques, whereas
- Appendix C illustrates the basic principles of feedback control.
- Chapter 9 is dedicated to force control techniques for robot manipulators

Artificial Intelligence
Robots

- Components
- Aspects
- Robot Locomotion
- Works
- Robot System vs AI Programs
- Application




Robotics
AI
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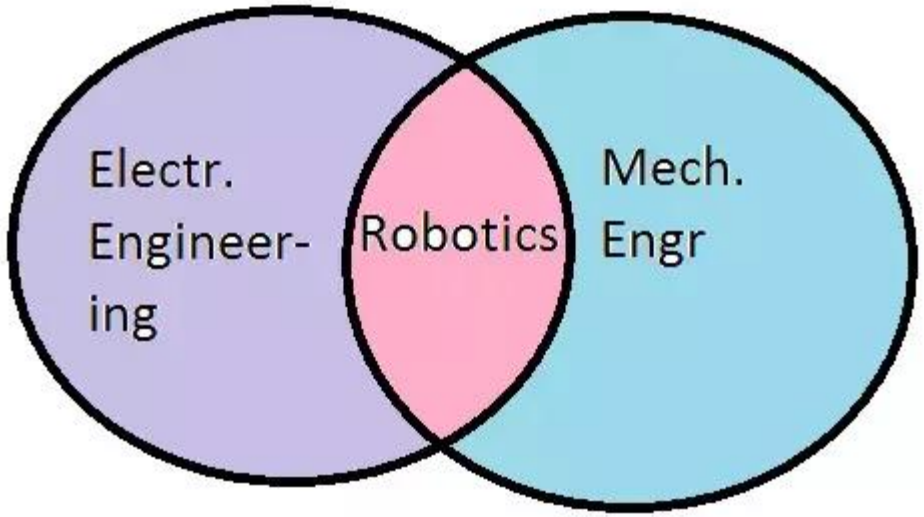
Intelligent Robots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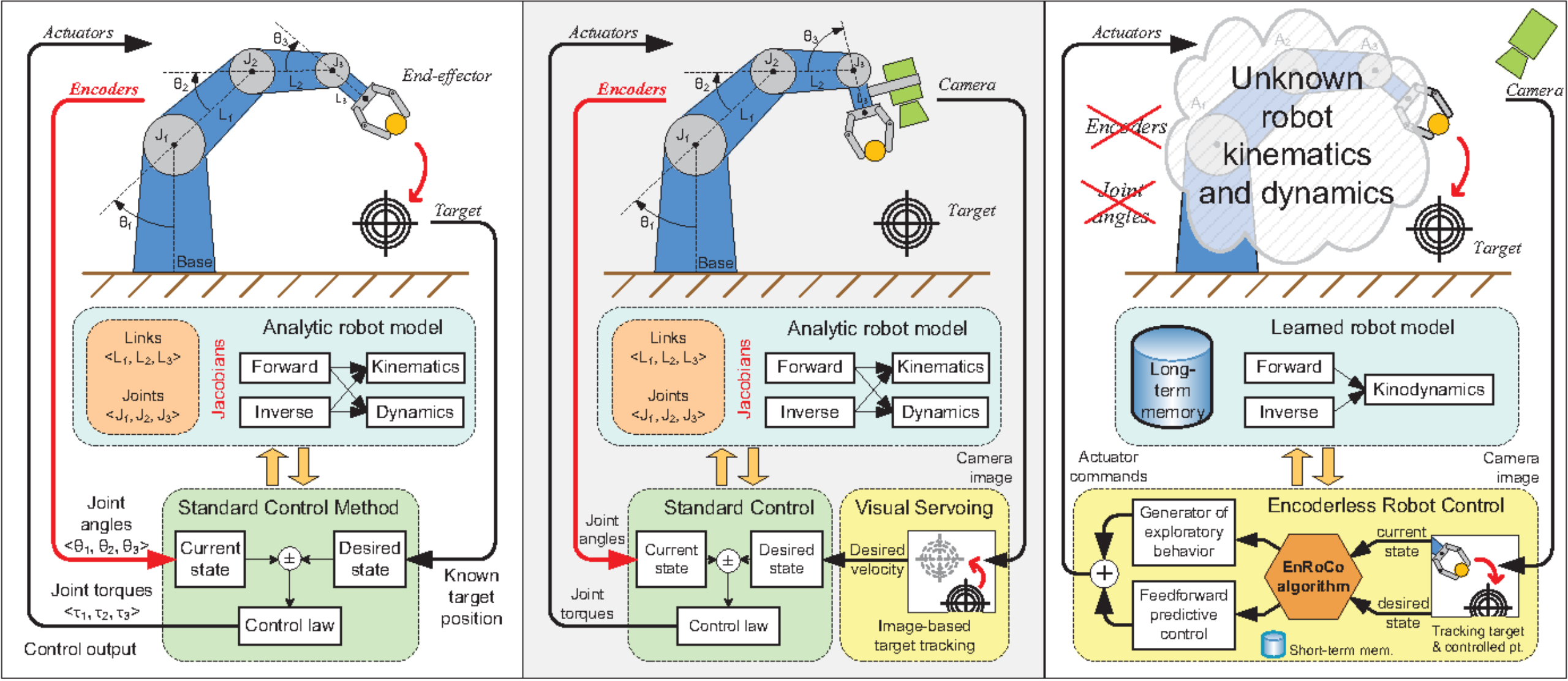

(a) Conventional encoder-based feedback control

(b) Conventional visual servoing control

(c) Proposed encoderless robot control