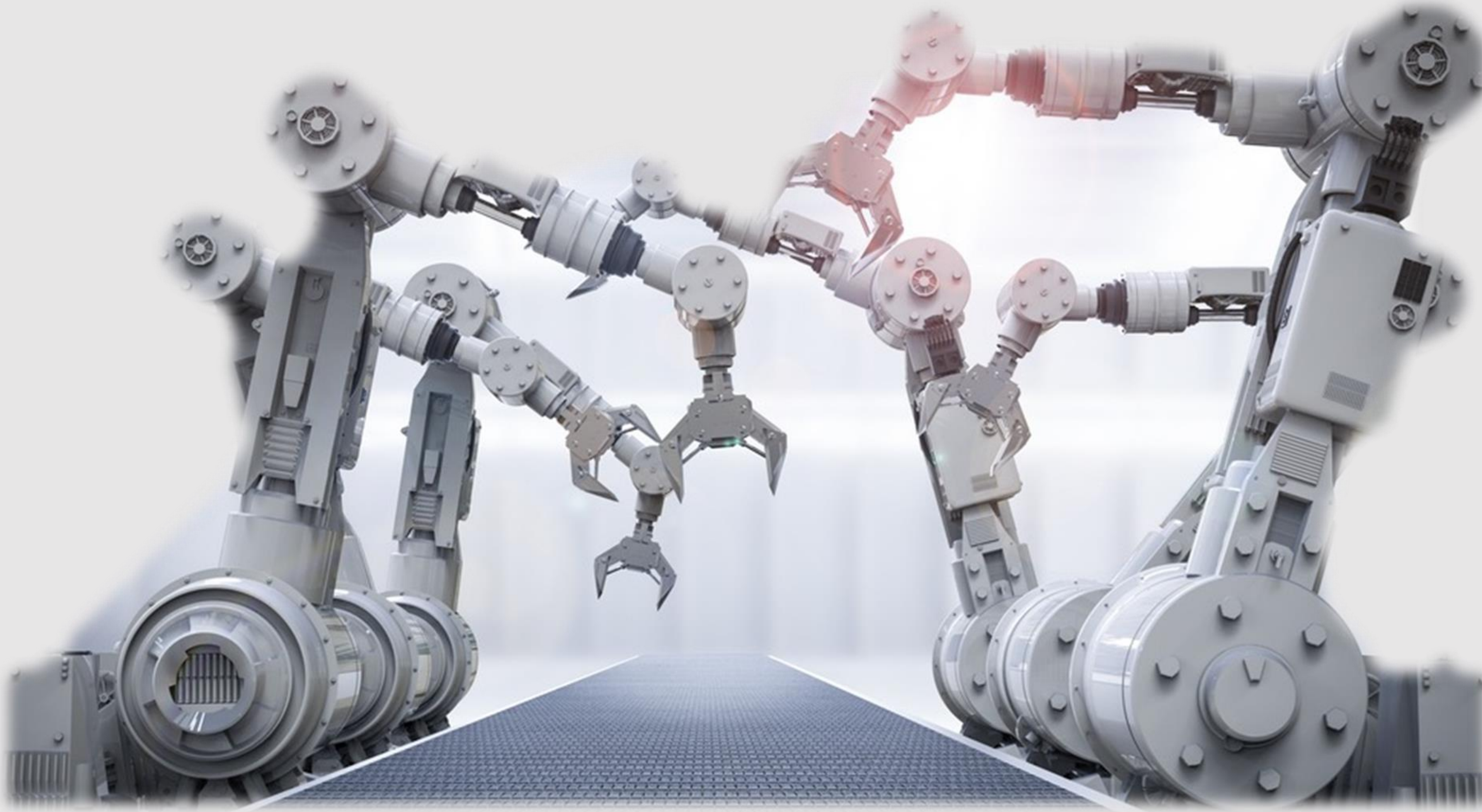
Introduction to Industrial Automation

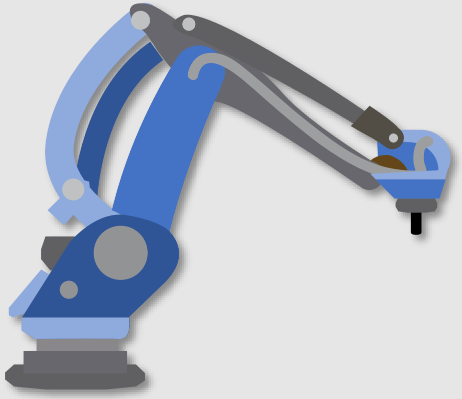


Prof Antonios Gasteratos

Basic milestones

2^{nd} industrial revolution :
- Electrification
- Mass production
- Transportstion

(~1840)



4^{th} industrial revolution :
- CyberPhysical Systems
- Artificial Intelligence
- IoT/Digital Twins

(2011)

USA

Europe/Asia/North America

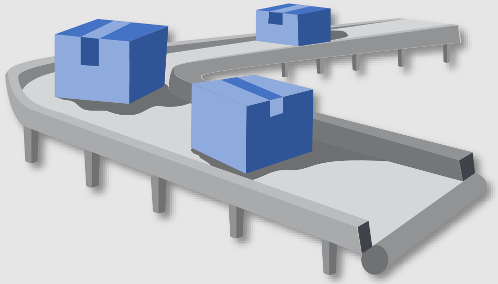
1. ---------- 2. ---------- 3. ---------- 4. ---------->

UK

USA/Europe/Japan

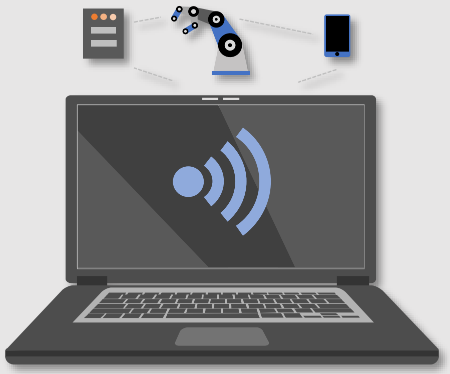
1^{st} industrial revolution:
- Factories
- Steam engines

(1760/1780)



3^{rd} industrial revolution
- Electronics/PLC
- Information Technology
- Robotics
- Automatization of production

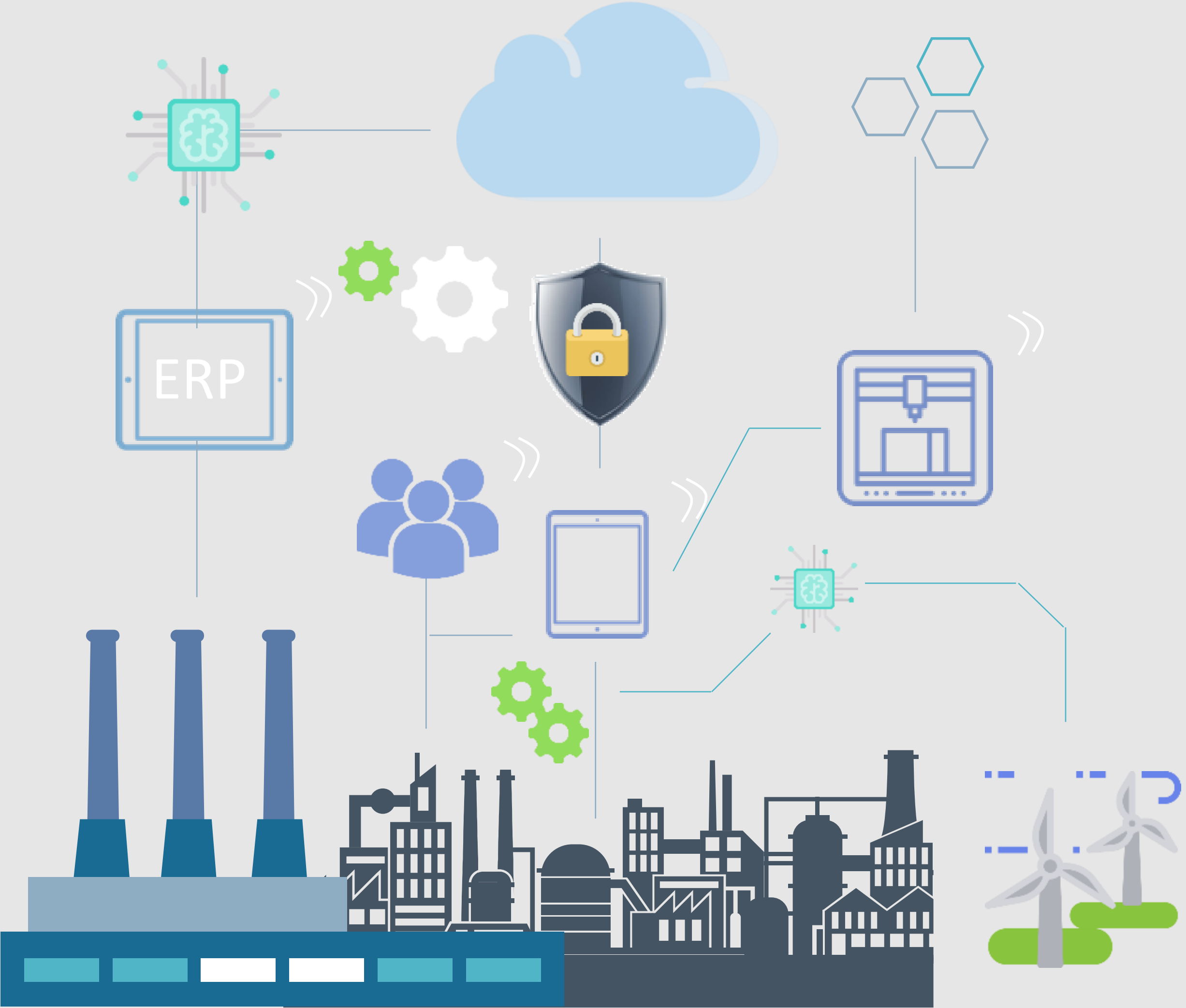
(1940)



What is automatization?

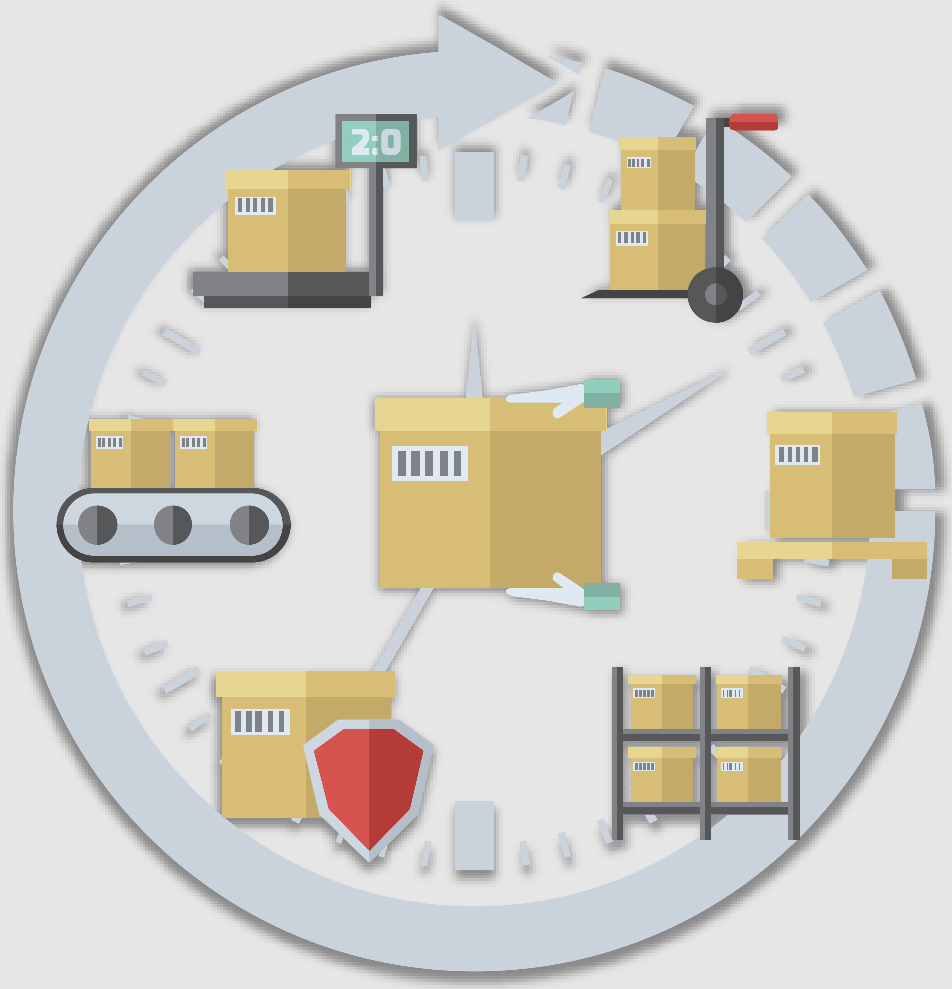
- Digitalization of Industry: connected machines, storage systems, and equipment, Cyber-Physical Systems (CPS)
- Interconnected corporate departments and associated companies.
- Intelligent machines with unrestricted data exchange.
- Real-time control and optimization of processes and strategies.
- Smart Factory: identification and tracking of products throughout the factory in real-time

Smart factory



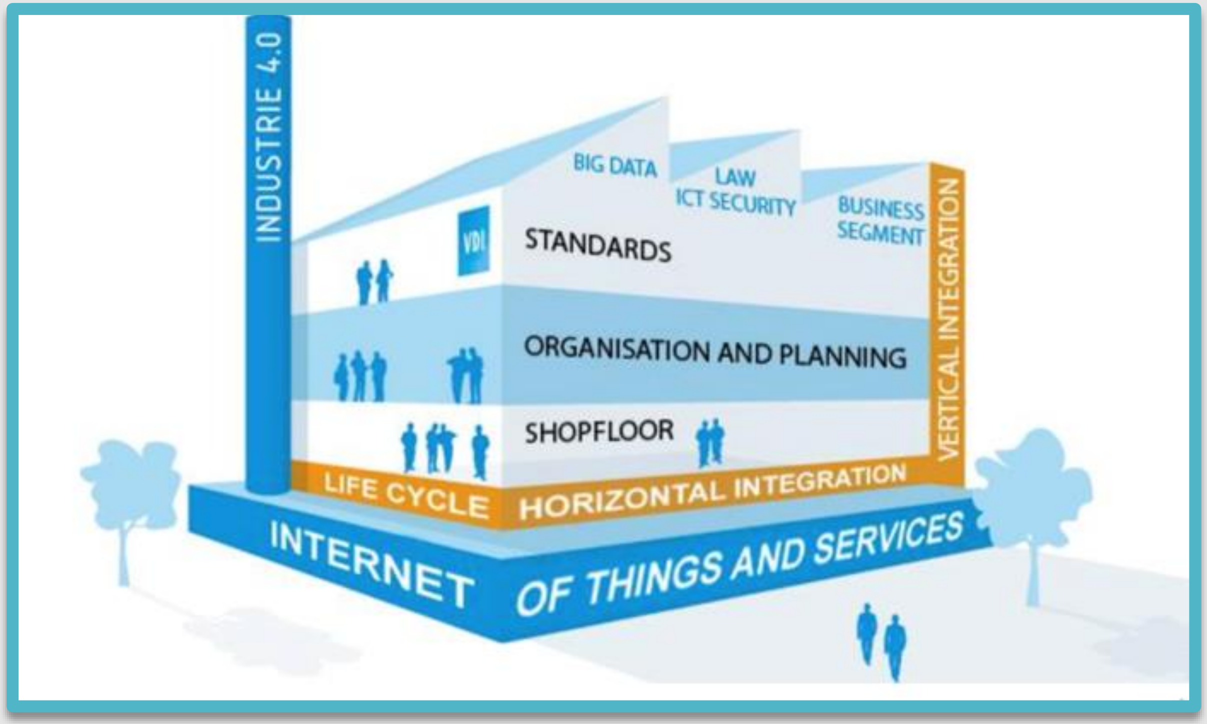
- Cloud computing
- Cybersecurity
- IoT
- Big data analytics
- Industrial metaverse
- Digital twins and simulation
- 3D printing
- Cobots
- Artificial intelligence

Why the transition to smart?



- Interoperability: the ability of machines, devices, sensors, and humans to connect and communicate with each other.
- Information transparency: the ability of information systems to create a virtual copy of the physical world, enriching digital models of installations with data from sensors.
- Technical assistance: the ability of support systems to assist humans, collecting and visualizing information in an understandable way capable of leading to well-founded decisions and solving urgent problems in a short period of time.
- Decentralized decision-making: The ability of cyber-physical systems to make decisions autonomously and perform their tasks as autonomously as possible.

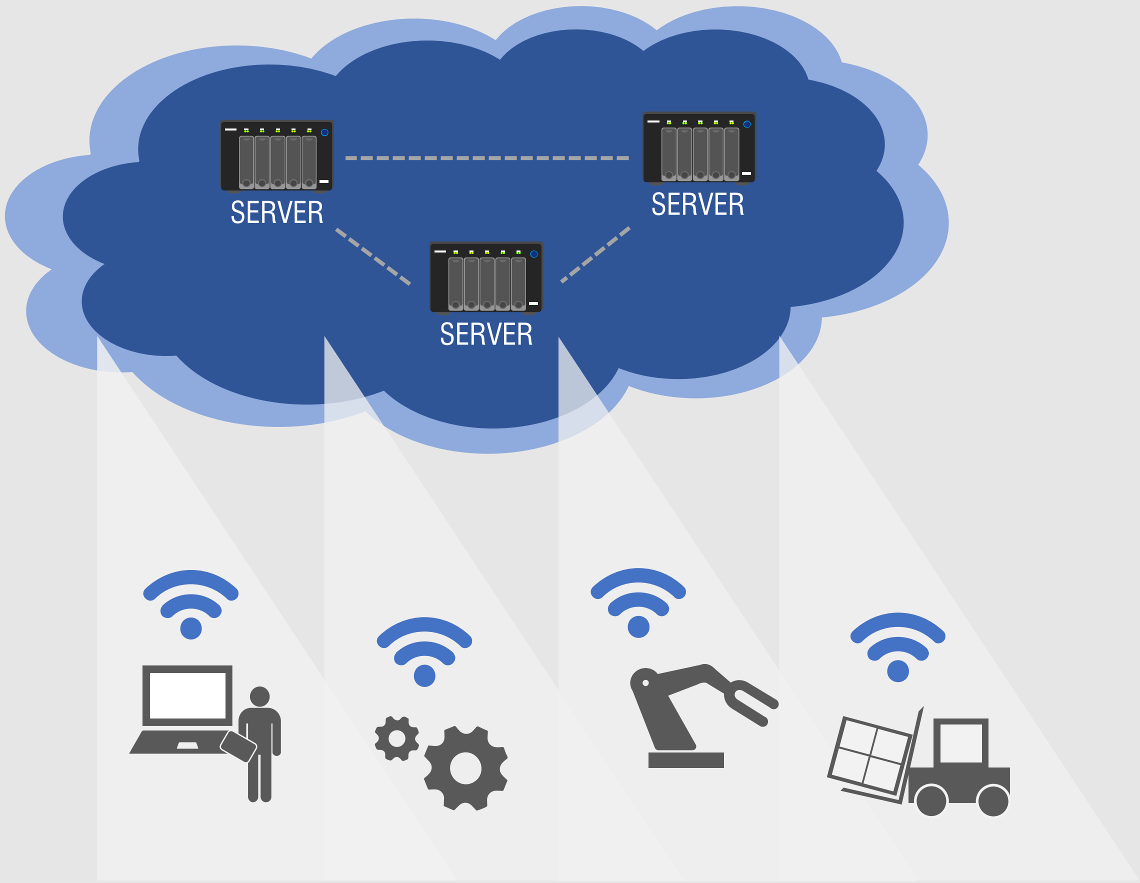
I4.0 characteristics



- **Vertical Integration** through smart devices interconnetion
- **Horizontal integration** through a global value web
- **Efficient technical solutions** throughout the entire value chain
- **Acceleration** by materializing innovative ideas

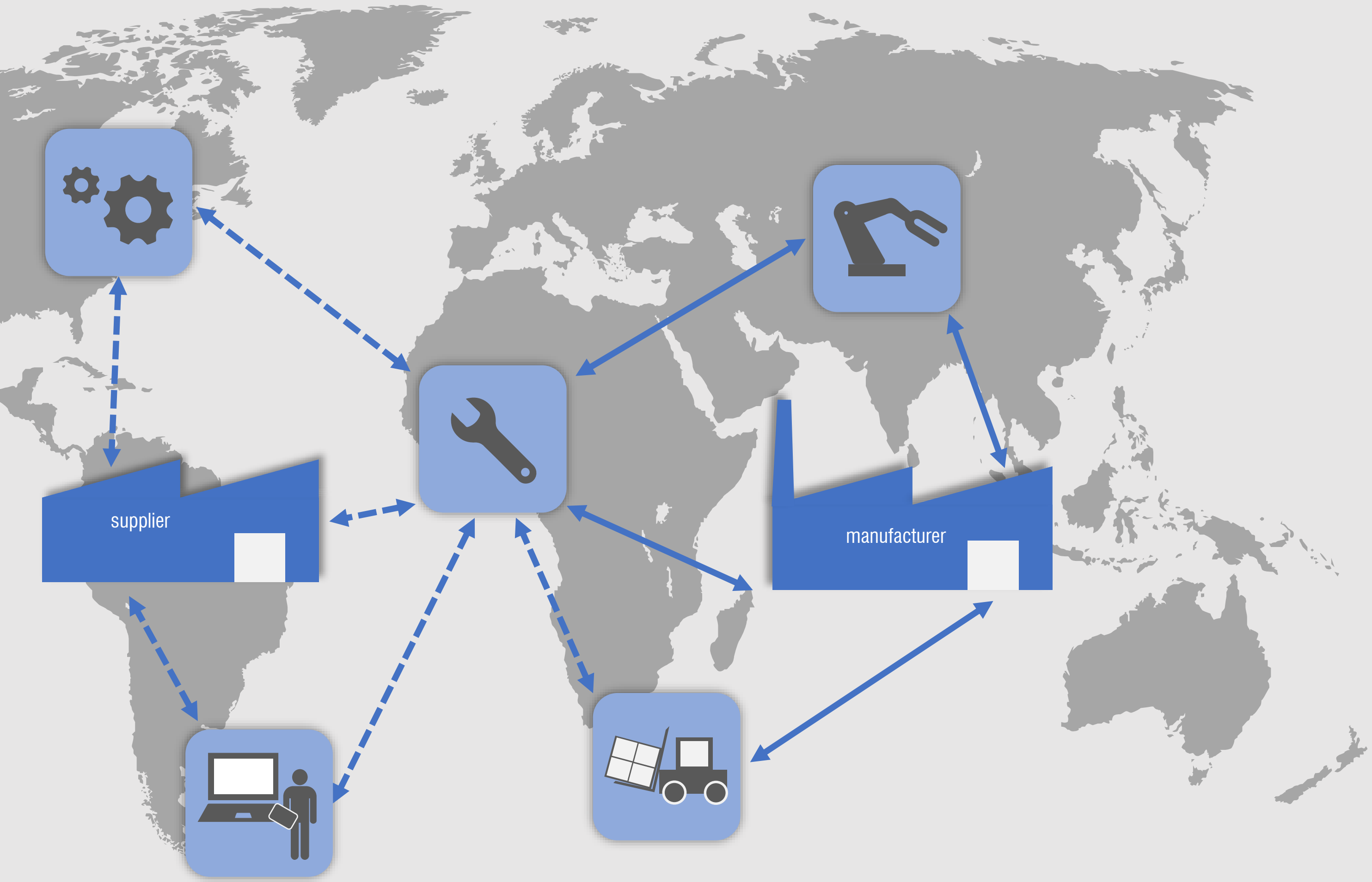
Vertical integration and networking

- The term "Vertical Integration" refers to modifications of interconnected industrial systems that approach different cases by applying alternative strategies.
- The regulatory framework of vertical integration concerns the factory. In the Smart Factory, production structures will no longer be discrete and predetermined. Instead, structures are defined by information management systems that automatically generate topologies on a case-by-case basis.



Horizontal integration through global value network

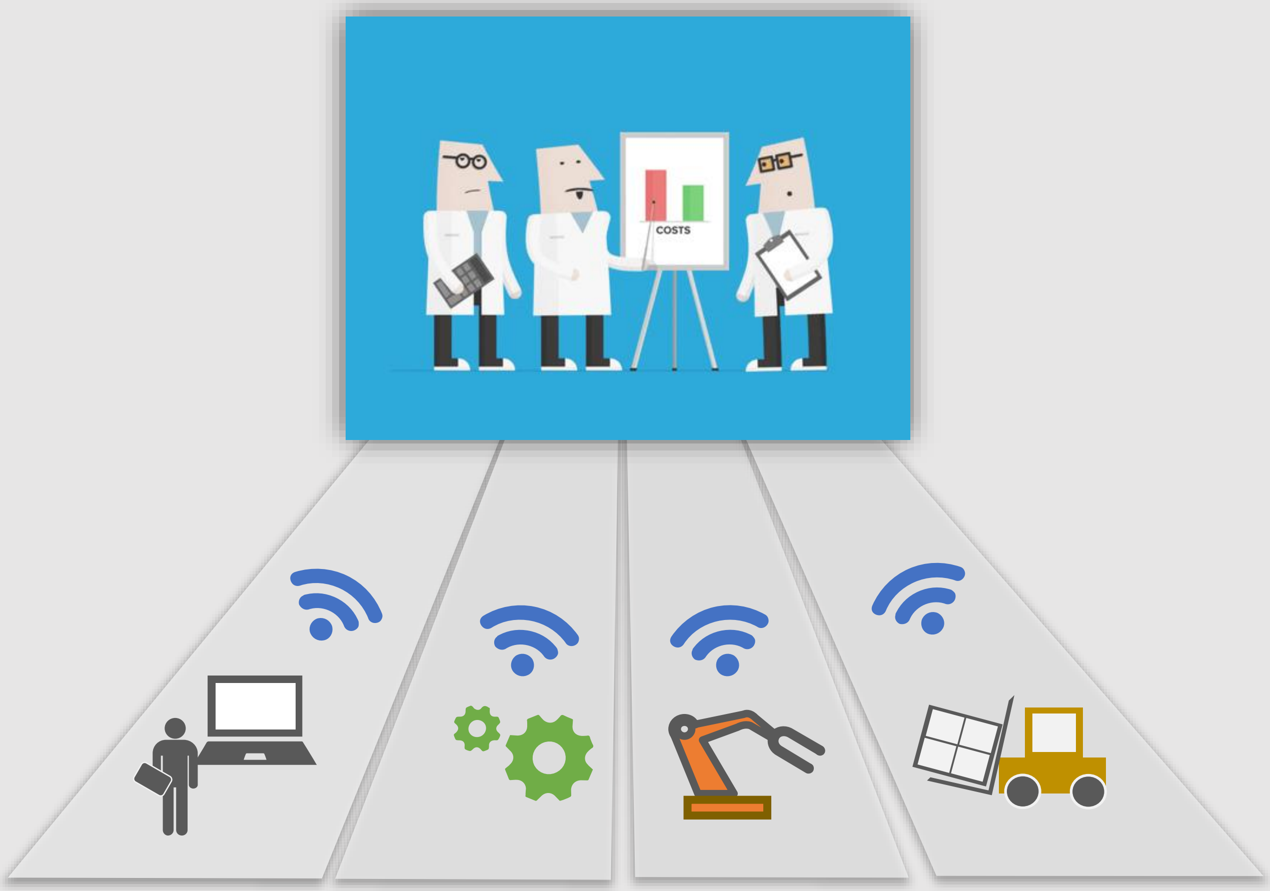
- The term "Horizontal Integration" is commonly known as an optimized flow of information and materials along a value chain, from suppliers to consumers.
- A horizontal integration system can manage, in real-time:
  - Products for delivery,
  - Formulation of supply plans, and
  - Communication with suppliers.



Transdisciplinary research throughout the entire value chain

The characteristic of interdisciplinary research concerns the integration of the entire value chain, including the product lifecycle.

It represents the mechanism that leverages data and available information from all stages of product lifecycle. Thus, the creation of new, flexible production processes is achieved through collected data, utilizing modeling and prototyping technologies prior to mass customization production.



Acceleration

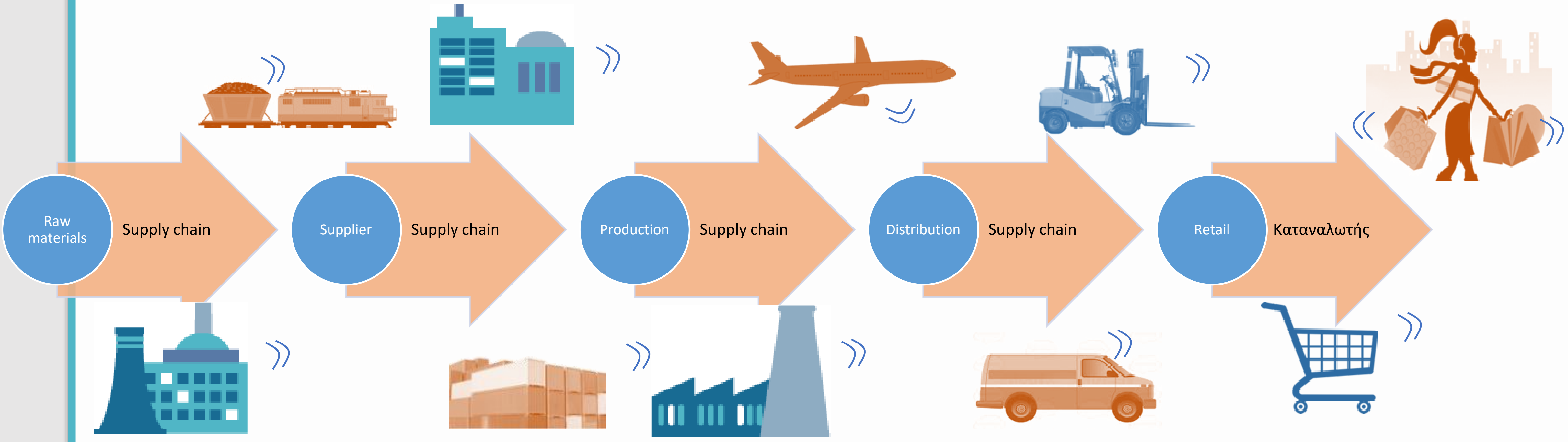
Acceleration through exponential technologies involves optimizing internal processes.

Acceleration is achieved by harnessing innovations that create personalized solutions, production flexibility, and cost savings during industrial processes.

Big data analytics

- By harnessing historical data, market trends, and external factors, AI-powered frameworks generate precise predictions, enabling organizations to optimize inventory levels, minimize stockouts, and mitigate excess inventory, optimize production processes and increase efficiency.

Advancements for enterprises



Challenges

Awareness
Many industries are misinformed or unwilling to adopt I4.0

Cybersecurity
Industrial IoT must inherently be secure against malicious attacks to ensure the smooth operation of production

Human
The introduction of new production models requires training of the human workforce to acquire suitable skills (upskill/reskill)

Investments
The implementation of Industry 4.0 solutions requires particularly significant investments.

Challenges

IT upgrade

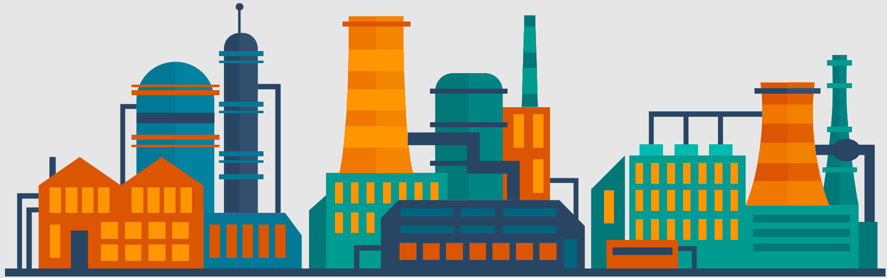
Upgrade the existing hw/sw solutions

Cooperation

Industry 4.0 requires the convergence of the Information Technology (IT) sector with Operational Technology (OT) and consequently collaborations in the respective fields

Regulation and Standardization

New standards and regulations needs to be adapted for Industry 4.0.



Flexible manufacturing systems (FMS)

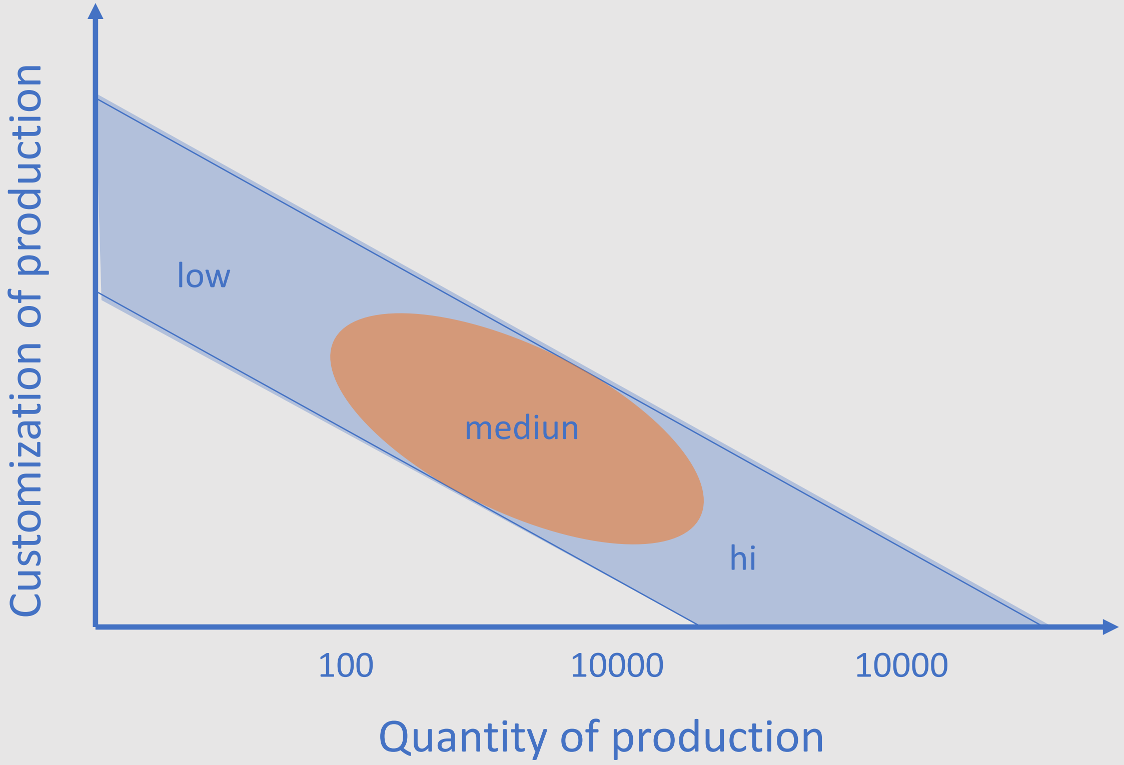
- A system consisting of multiple programmable machines connected by an automatic material handling system

Why FMS?

- Issues such as inventory reduction, market responsiveness time to meet customer demands, flexibility to adapt to market changes, cost reduction of products and services to gain more market share, etc., have made it almost mandatory for many companies to switch to flexible manufacturing systems (FMS) as a sustainable means to fulfill the above requirements, consistently generating good quality and economically efficient products. FMS is essentially an automated set of numerically controlled machine tools and material handling systems capable of performing a wide range of manufacturing tasks with rapid tool changes and instructions

Where to use FMS?

- The FMS is more suitable for the medium volume and medium variety production range.
- The reason FMS is called flexible is that it is able to process a variety of different product parts simultaneously at various workstations, and the combination of parts and production quantities can be adjusted according to changes in demand patterns.

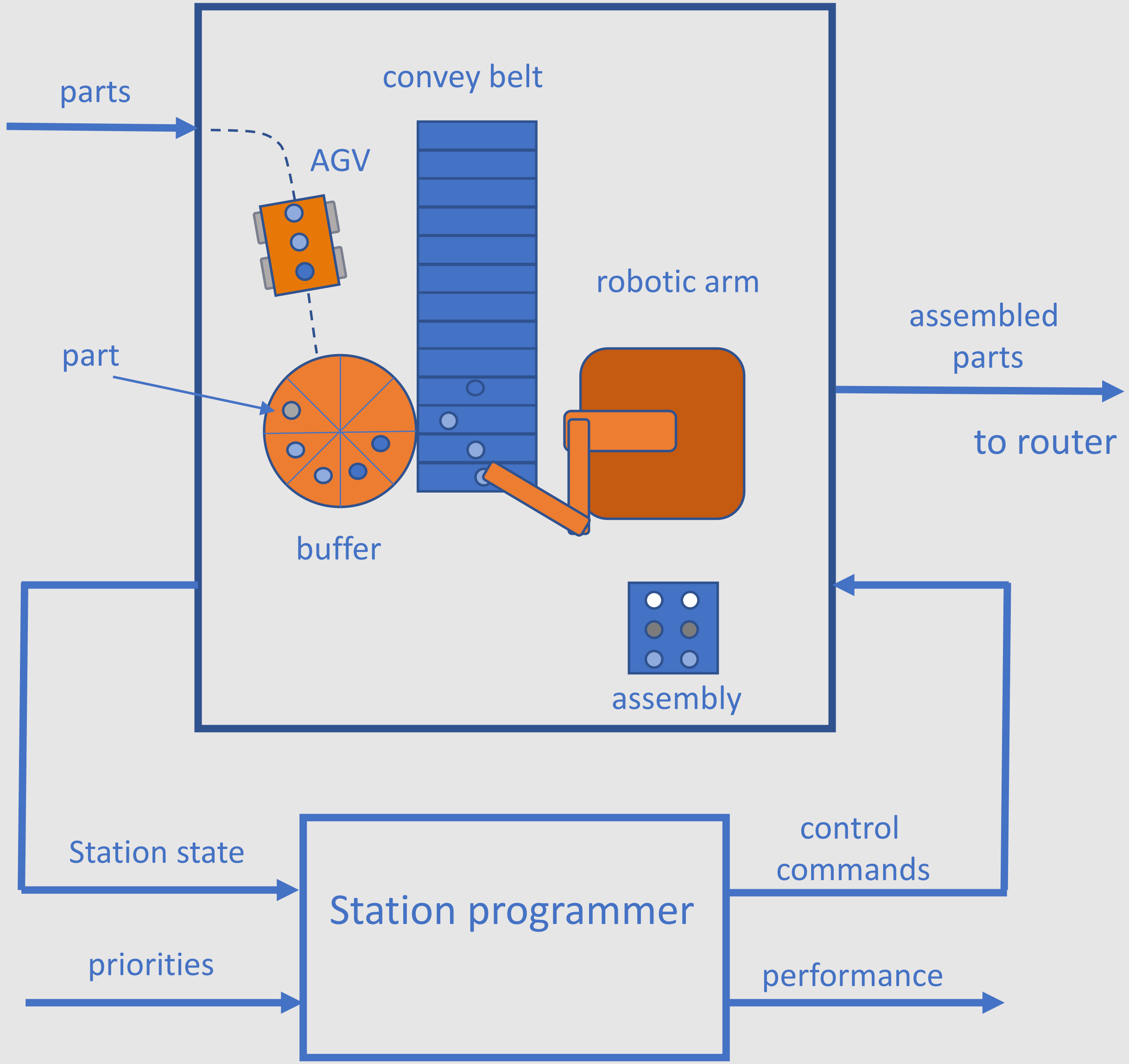


What is flexibility?

- Flexibility is a characteristic that allows a mixed model assembly system to handle a certain level of variations in product part or style without any production interruption due to changes between models. Flexibility measures the ability to adapt "to a wide range of possible environments." To be flexible, a manufacturing system must have the following capabilities:
  - Identification of various production units for proper execution
  - Quick change of operating instructions on computer-controlled production machines
  - Swift alteration of physical settings of components, tools, and other work units.

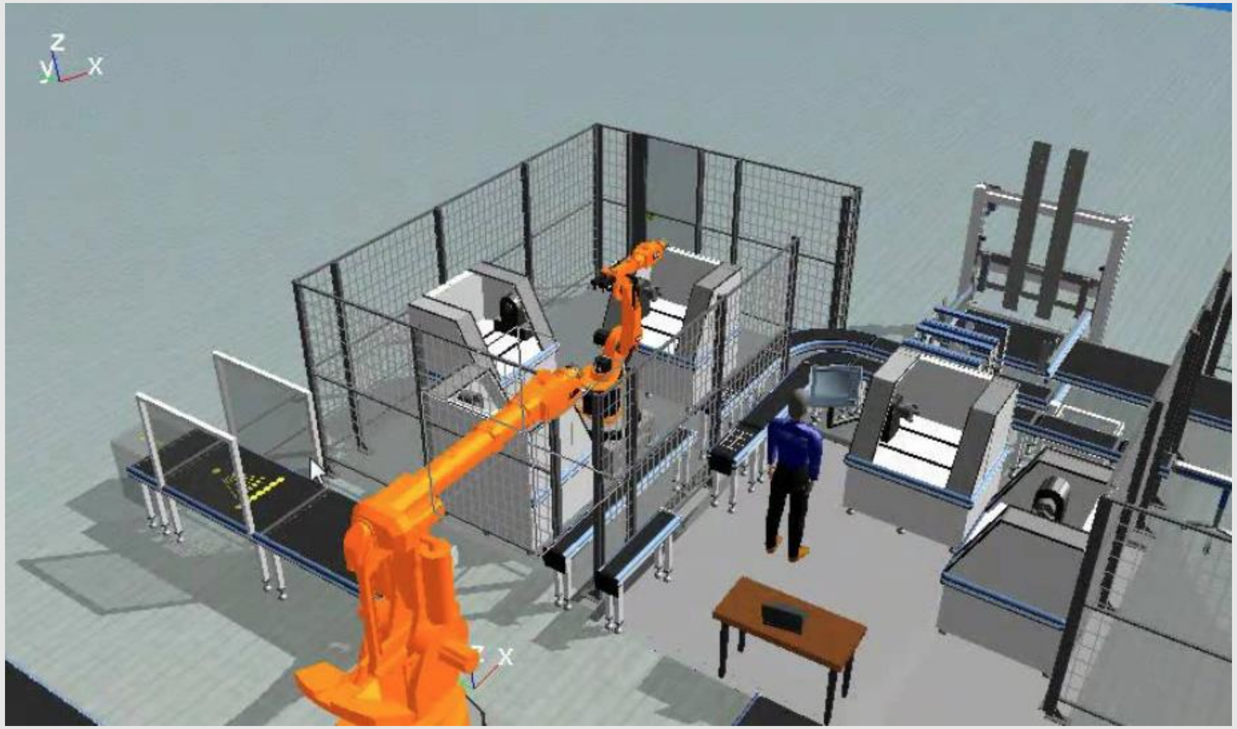
Basic parts of an FMS

- Work stations
- System for automatic manipulation and storing of materials
- Computer-based control system



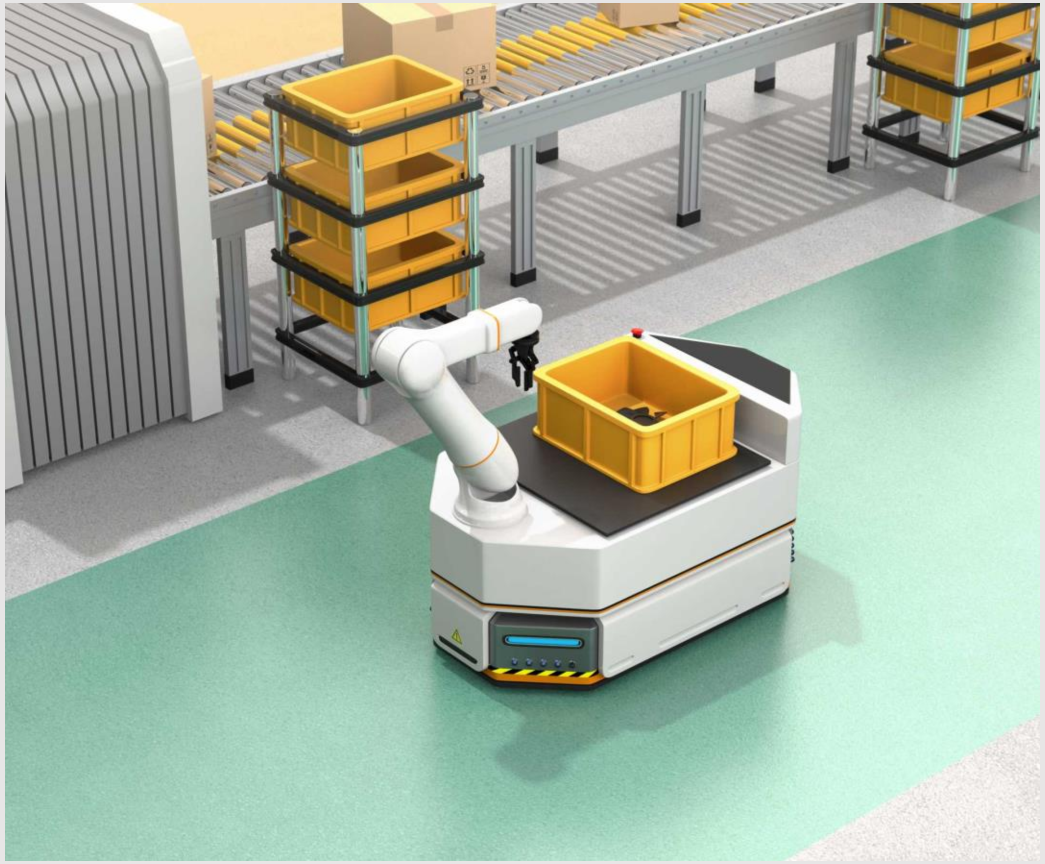
Work-stations

- Loading/unloading stations
- Processing stations
- Other processing stations
- Assembly station
- Other stations and equipment



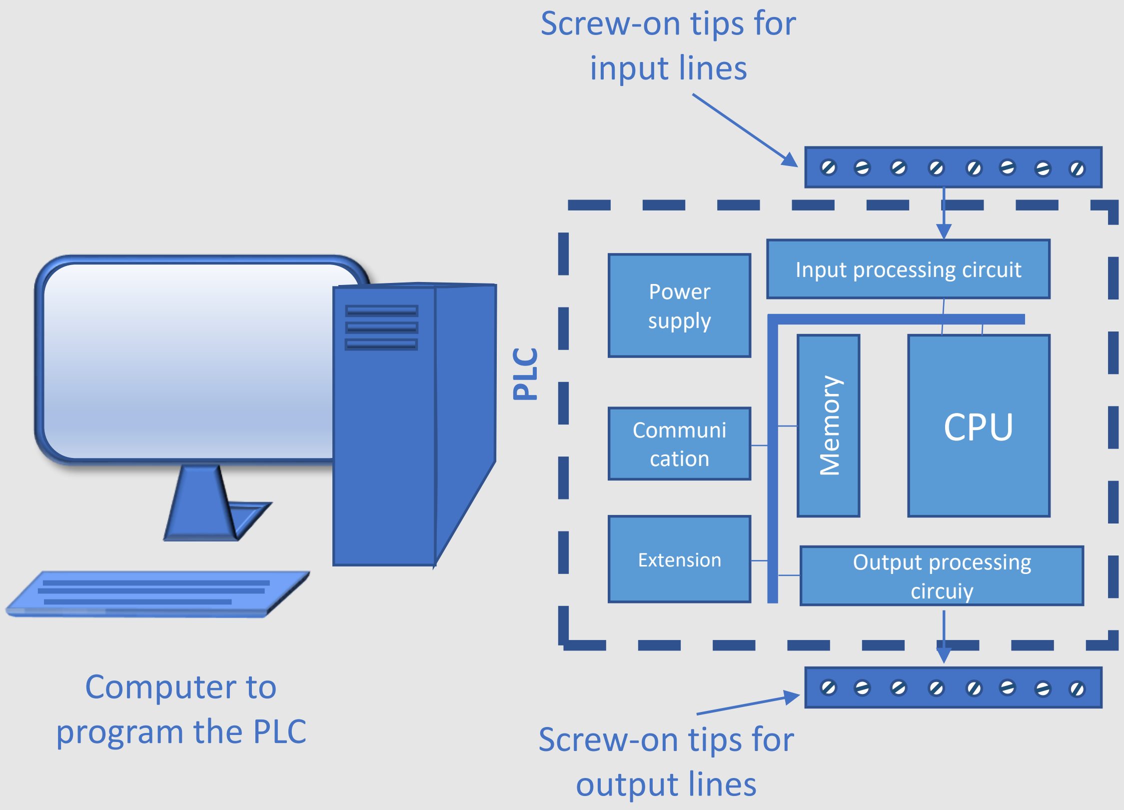
Automated material handling and storage system

- Conveyor belts
- Cranes
- AGVs



Computer-based control system

- The FMS includes a distributed computer system to which workstations, material handling systems, and other material elements are connected.
- A typical FMS computer system consists of a central computer and microcomputers. Microcomputers control individual machines and other components. The central computer coordinates the activities of the components for the smooth overall operation of the system.

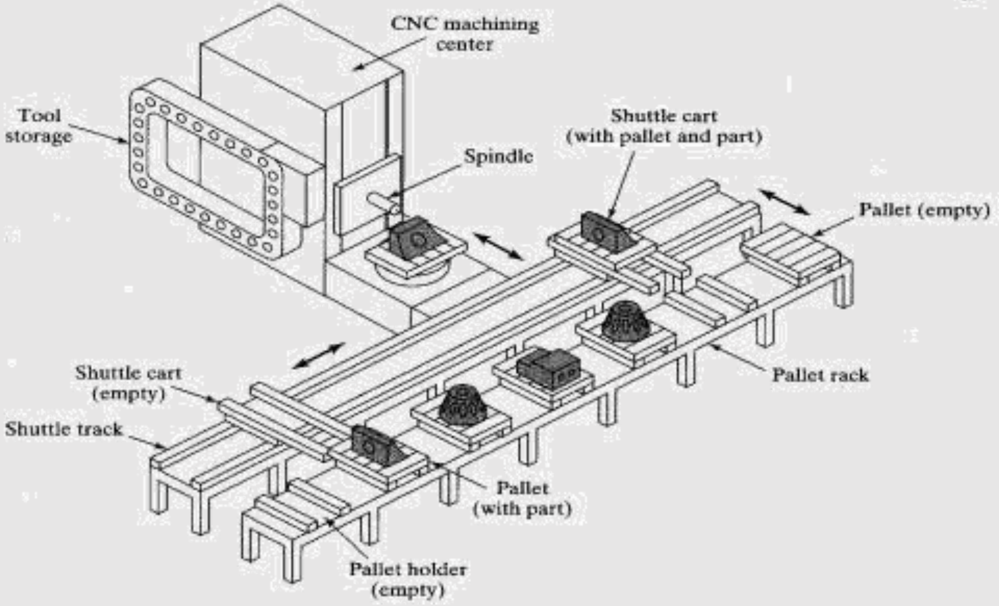


FMS categories

- FMS can be categorized based on the number of machines in the system. The following are typical categories:
  - Single-cell machine (Type I A)
  - FMS (typically Type II A)

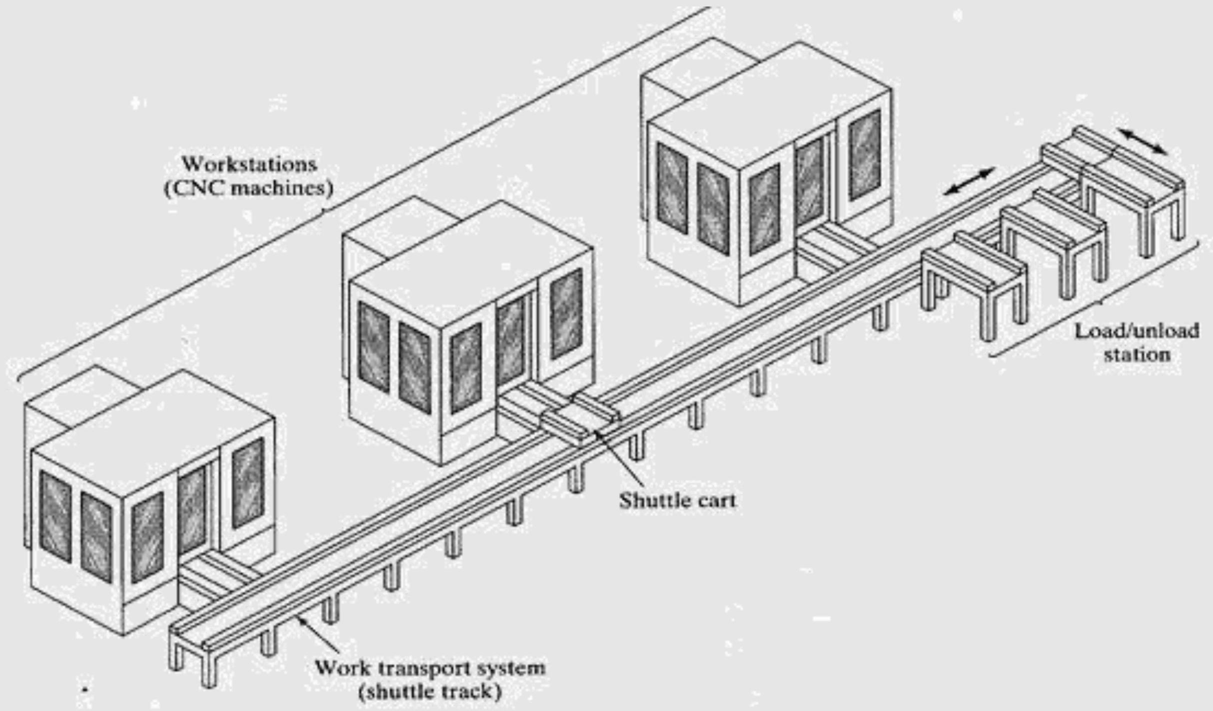
Single-Machine Cell (typically Type I A)

- A single-cell machine consists of a machining center (CNC or 3D printer) combined with a parts storage system for seamless operation.
- Finished parts are periodically unloaded from the parts storage unit and raw parts are loaded.



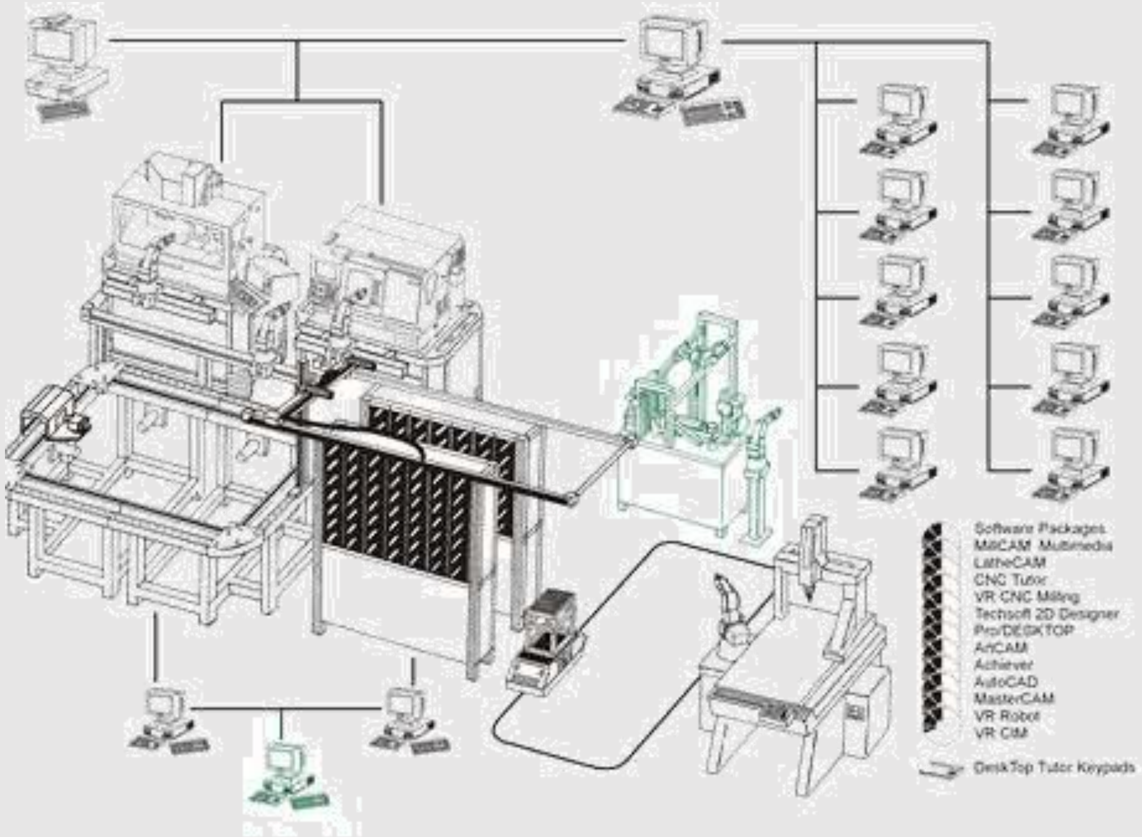
Flexible Manufacturing Cell (typically Type II A)

- A flexible manufacturing cell consists of two or three processing workstations (usually CNC machining centers) along with a parts handling system.
- The parts handling system is connected to a loading/unloading station.



Flexible Manufacturing System (typically Type II A)

- A flexible manufacturing system consists of four or more workstations mechanically linked with a common parts handling system and electronically controlled by a distributed computer system.



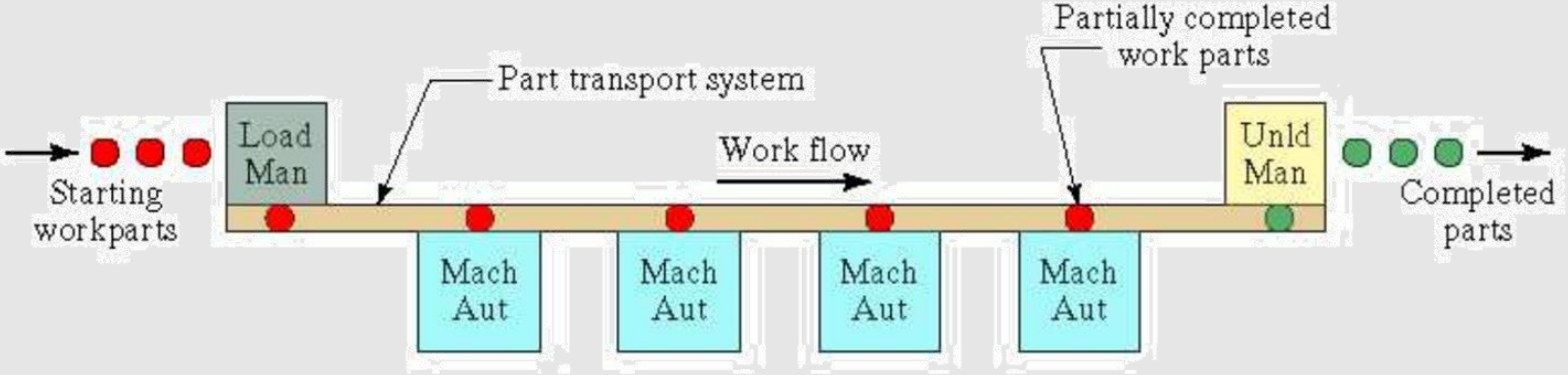
Types of FMS

- Series
- Random
- Special
- Custom

Configuration of FMS

- Linear
- Loop
- Ladder
- Open-field
- Robo-centric

Linear


Partially completed
work parts
Part transport system
Load
Man
Work flow
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Man
Starting
workparts
Completed
parts
Mach
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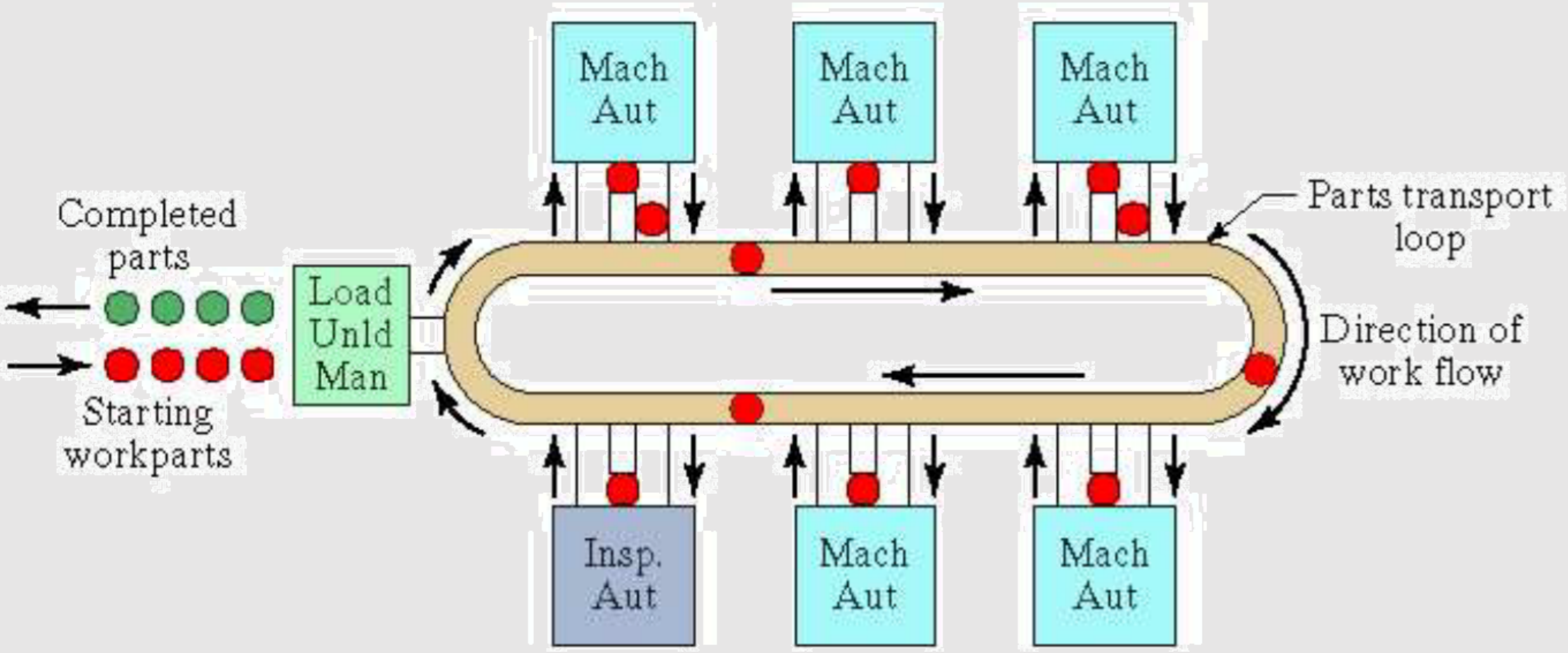
Loop


Mach
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Parts transport
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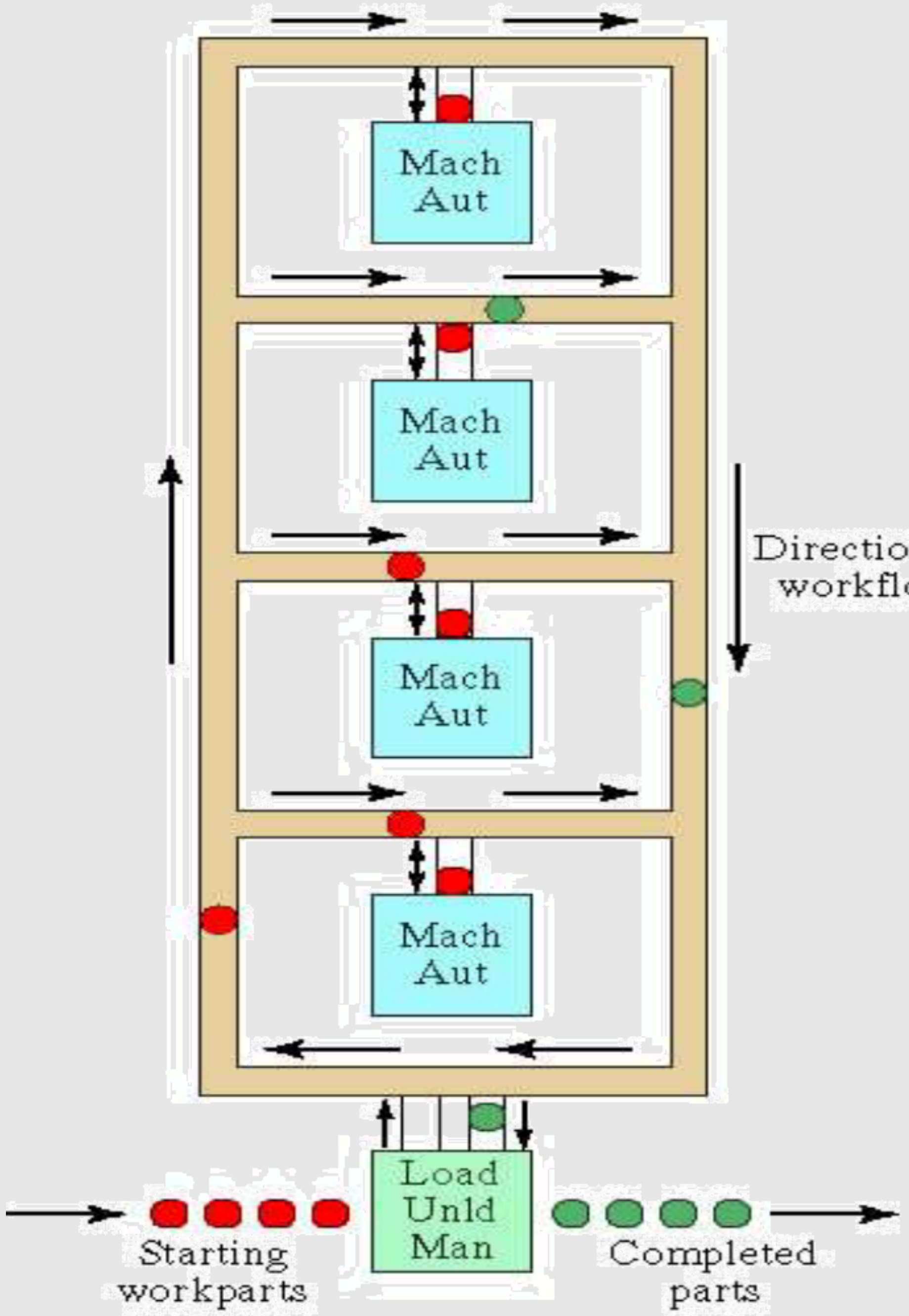
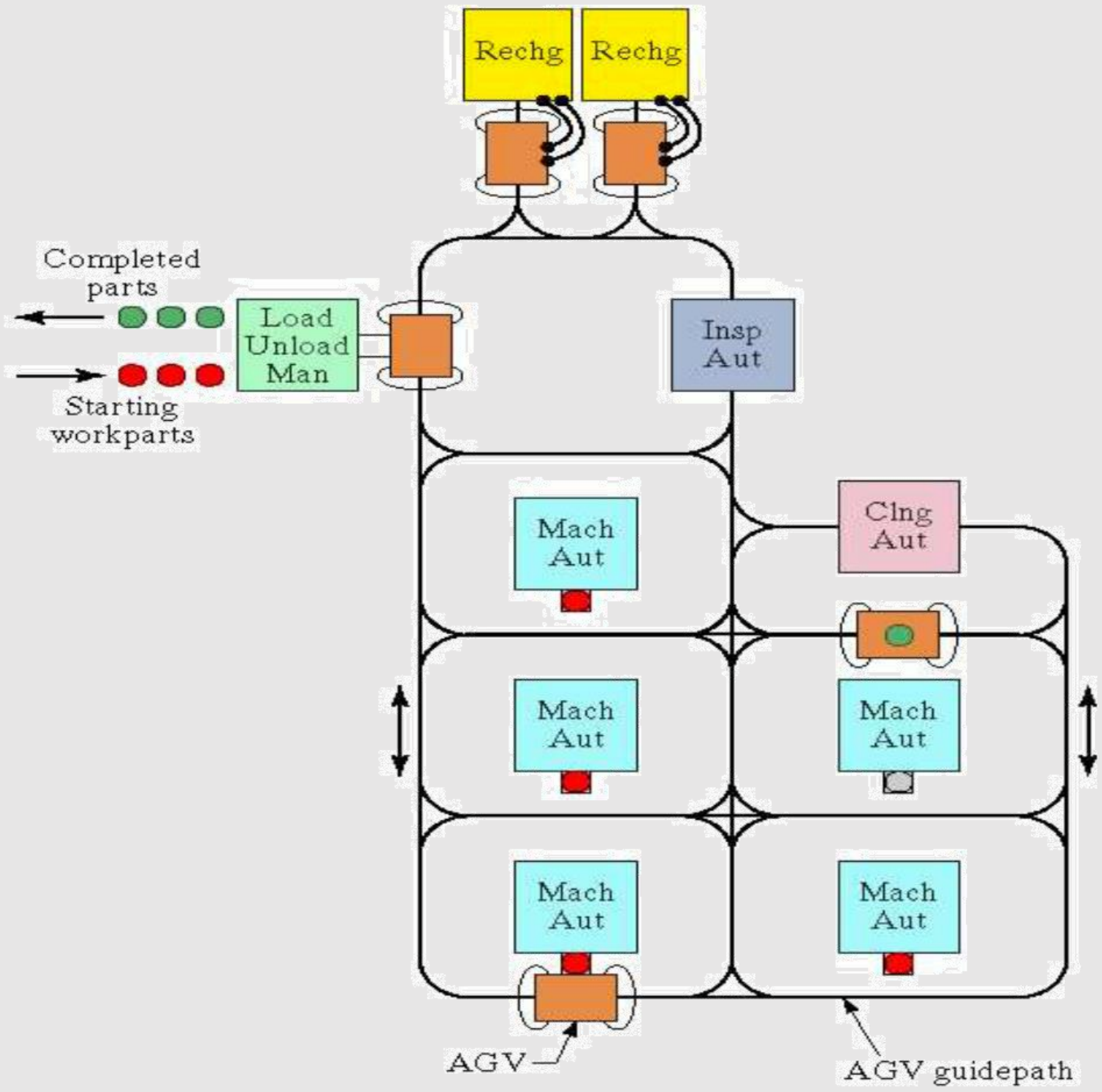
Ladder



Mach Aut
Mach Aut
Mach Aut
Mach Aut
Direction of workflow
Load Unld Man
Starting workparts
Completed parts

Open-field



Rechg
Rechg
Completed parts
Load Unload Man
Starting workparts
Insp Aut
Mach Aut
Clng Aut
Mach Aut
Mach Aut
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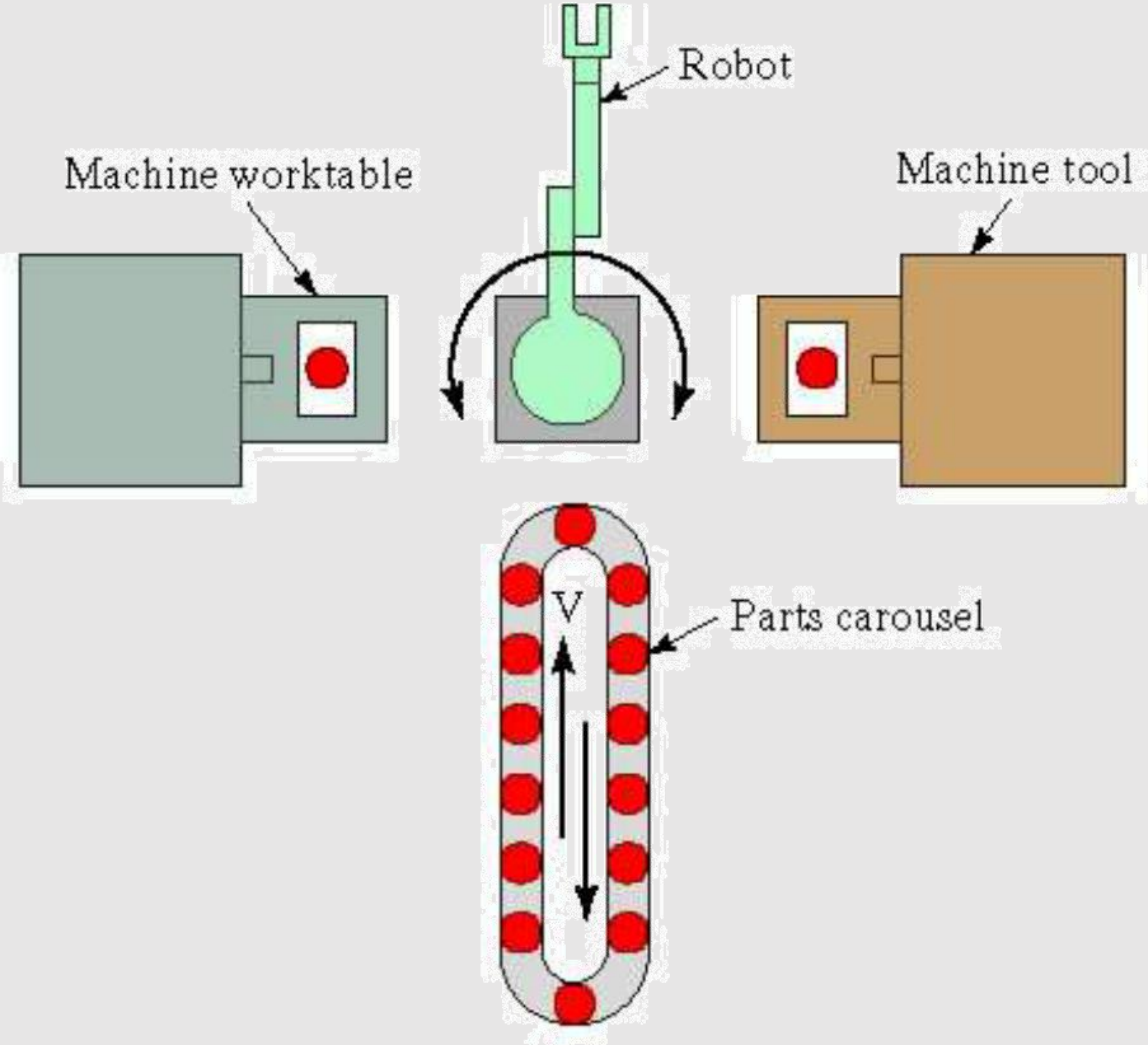
Mach Aut
AGV
AGV guidepath

Robo-centric



Advantages of FMS

1. Ideally suited for external changes, such as changes in product design and production system.
2. Optimize manufacturing and product delivery cycle time.
3. Reduce production costs.
4. Robust to internal changes, such as faults, etc.
5. Produce at a lower cost per unit.
6. Increase productivity.
7. Enhance machine efficiency.
8. Improve quality.
9. Increase system reliability.

Advantages of FMS (continued…)

1. Reduce setup and queue times
2. Improve performance
3. Decrease product completion time
4. More efficient use of labor force
5. Enhancement of product scheduling
6. Generate variety of items
7. Provide capability to serve multiple customers simultaneously
8. Adapt to CAD/CAM operations
9. Reduce spare parts inventory

Disadvantages of FMS

1. High initial installation cost
2. High operating cost
3. Significant operational design activity
4. Substantial operational planning
5. Demand for specialized labor force
6. Complex system, specialized maintenance, and spare parts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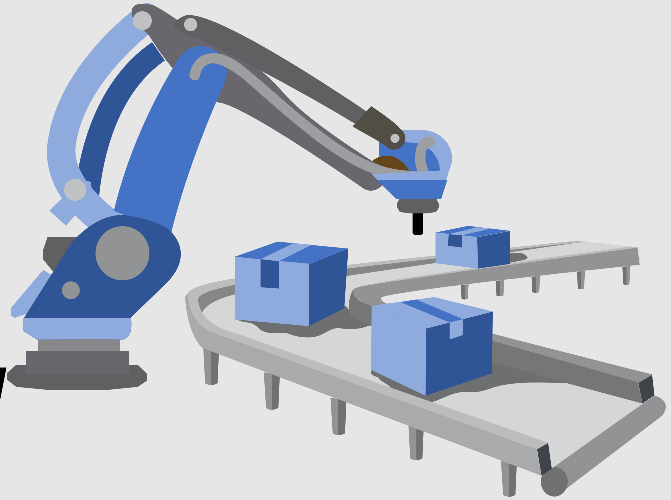
Robotics today

The technological sector that involves design, implementation, operation and application of robots

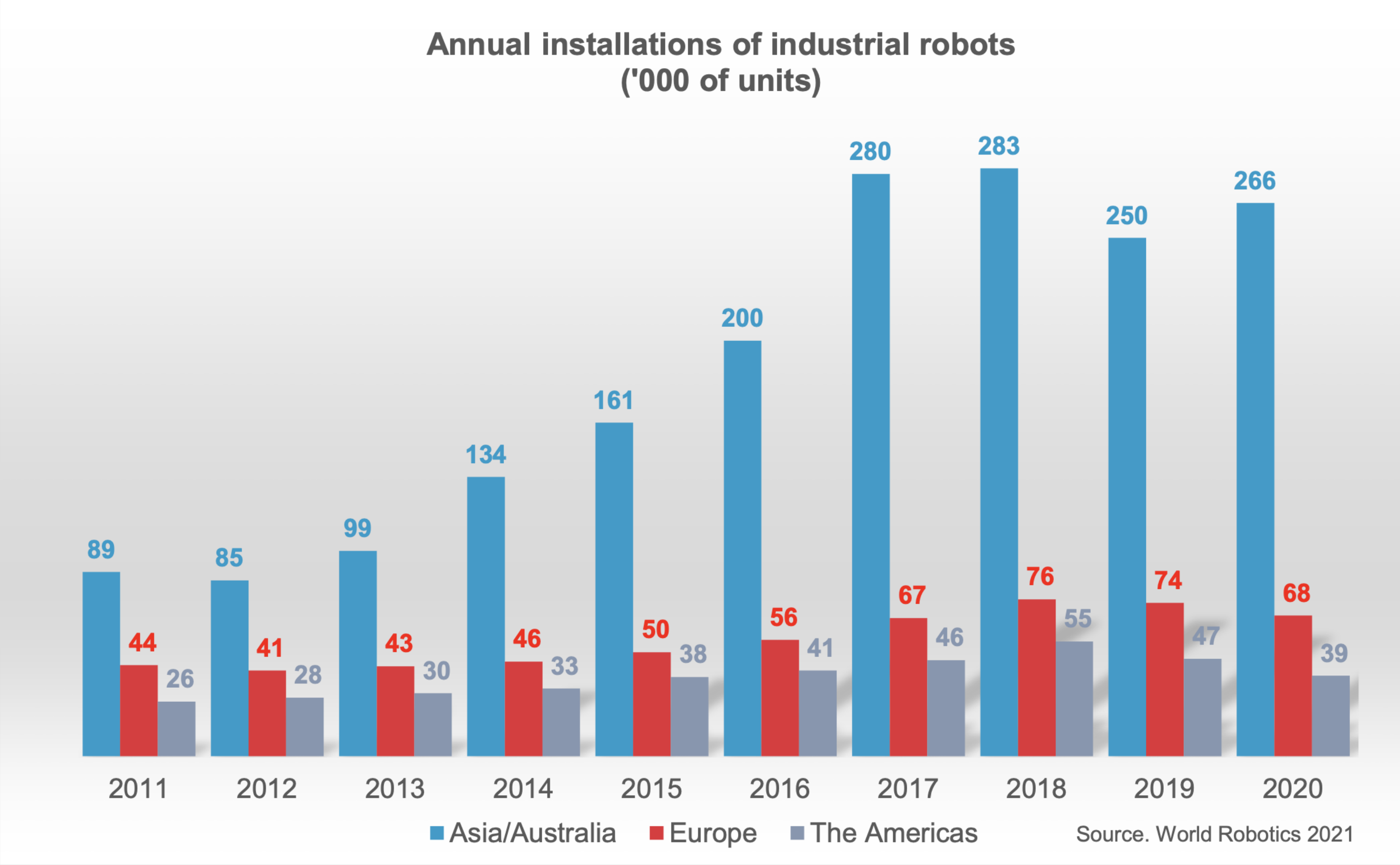
What is a robot?

- The Robotic Industries Association (RIA) defines a robot as follows:

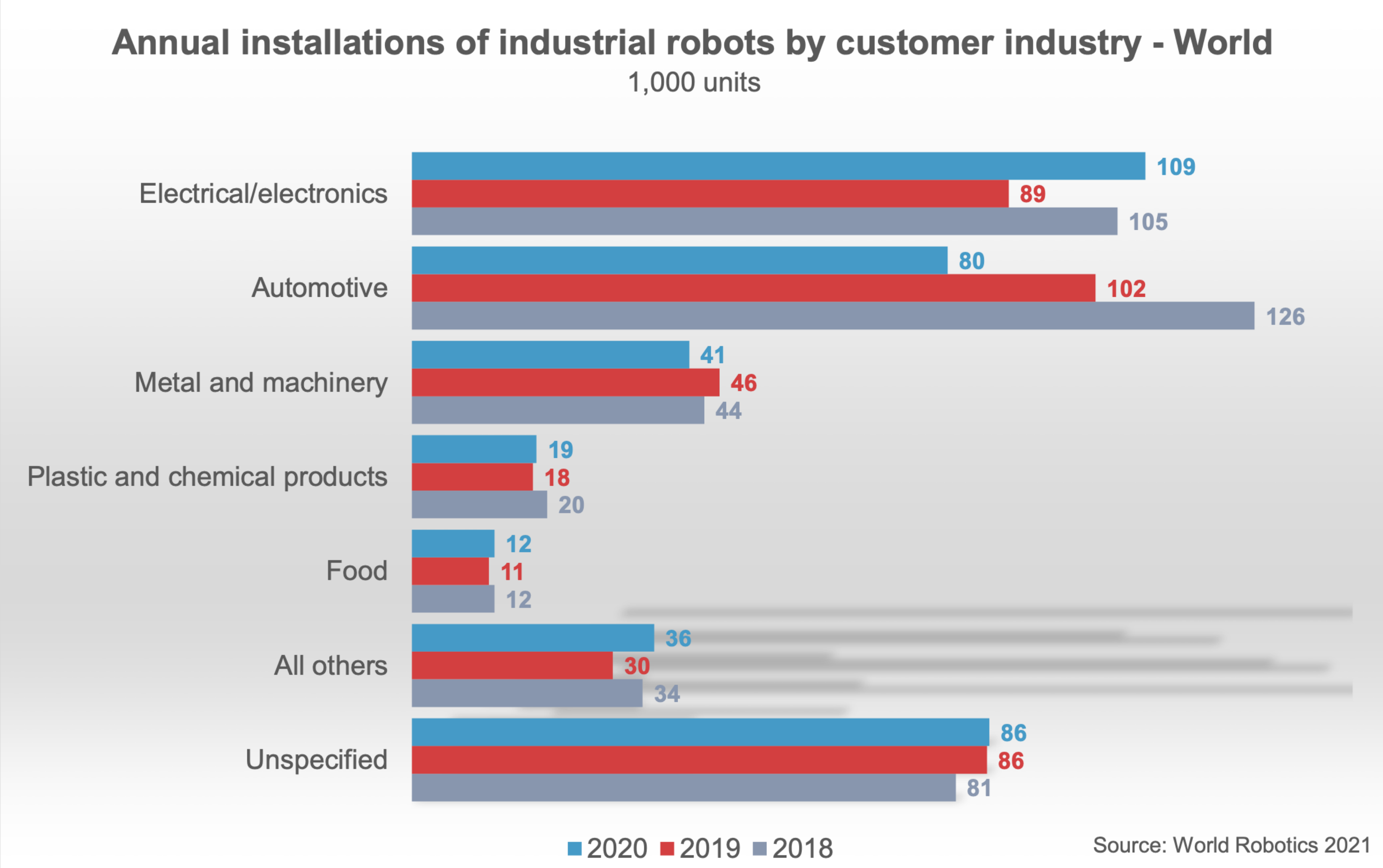
- *A robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks*



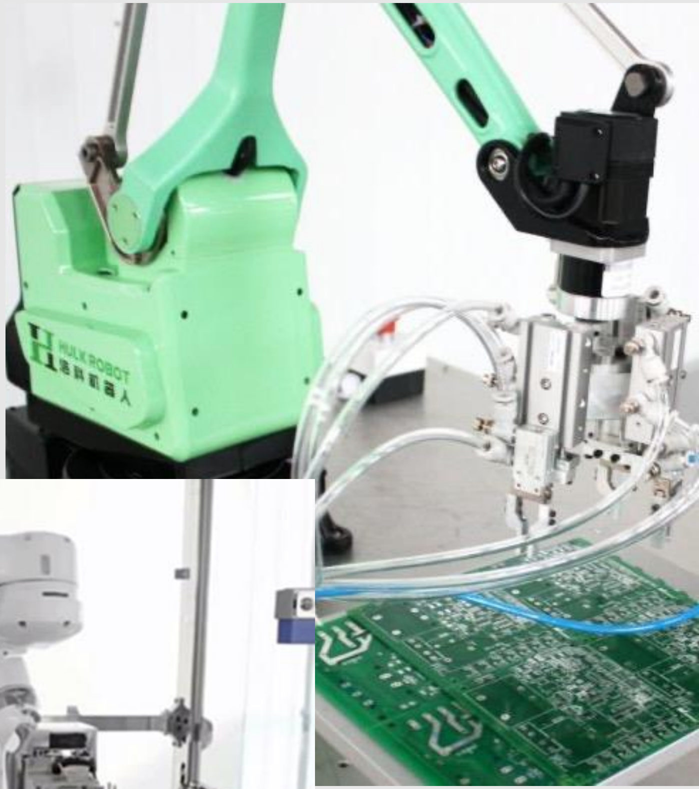
Industrial robot installations

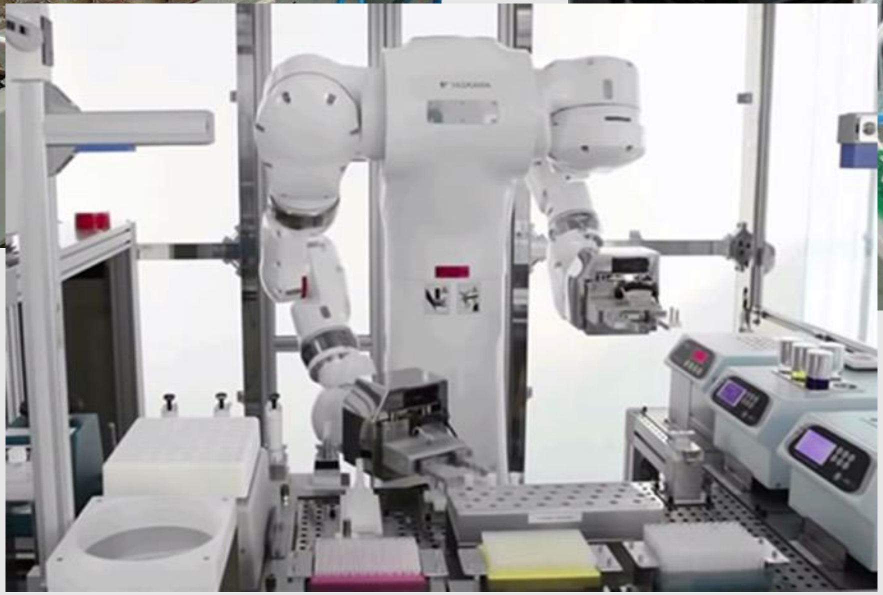


Yearly installations of industrial robots per customer

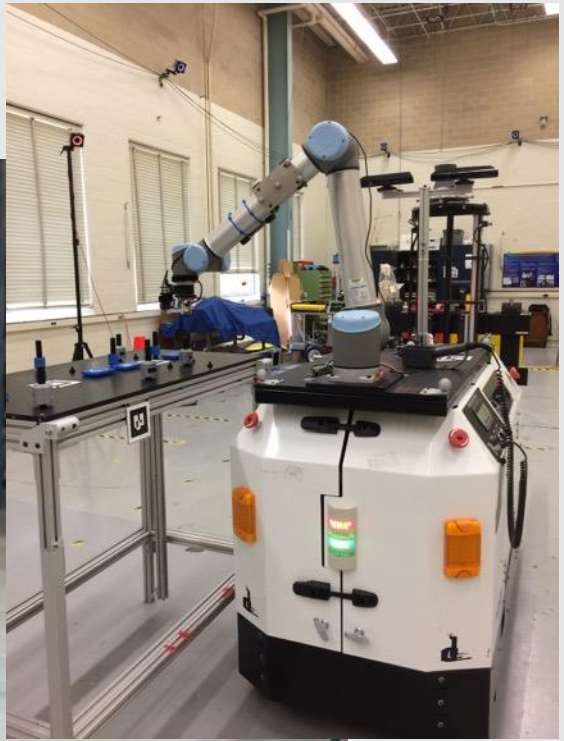


Use of robotic arms in industry



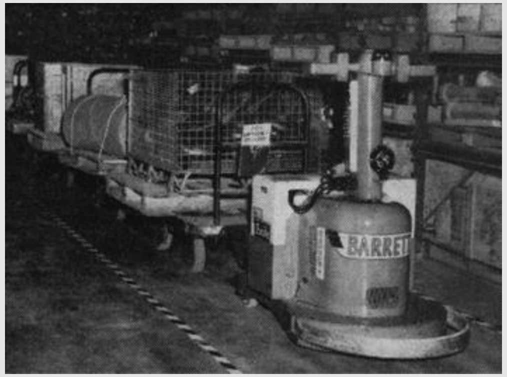


Use of AGVs in industry

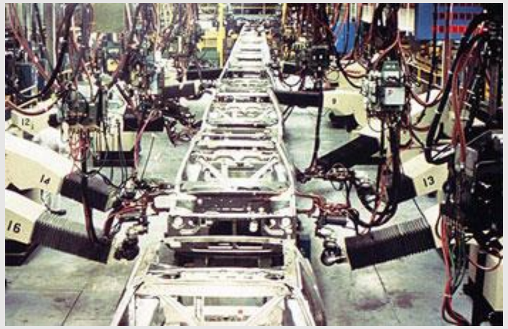


Brief history

- Unimate introduced the first industrial robotic arm in 1961, it has subsequently evolved into the PUMA arm.
- The first automated guided vehicle arrived in the early 1950s and was little more than a glorified tow truck, albeit one that did not require a driver or a fixed rail system, navigating instead by following a track of wires embedded in the factory floor that generated a magnetic field.



Brief history



- In 1969, it rebuilt its Lordstown, Ohio plant installing Unimate spot welding robots. Capable of production speed never before achieved, the robots built 110 cars per hour - more than double the rate of any automotive plant in existence at the time
- The first internationally-known company to adopt AGVs was Volvo, which installed 280 computer-controlled vehicles in their Swedish automobile plant in 1973. This replaced their traditional conveyor assembly line, and was eventually marketed to other manufacturers.

Brief history

- 1970s: Robotic arms improved with sensory systems: force sensors, basic vision.
- 1980s: Efforts to improve performance: control, feedback + redesign.
- 1990s: Transformable robots for assembly, moving and walking autonomous robots, vision control, first underwater robots.
- 2000s: First household robots (Roomba), first attempts for driverless cars (DARPA grand challenge), SLAM.
- 2010s: Flying robots (drones), humanoid (DARPA robotics challenge), deep learning networks.
- Today: Biologically inspired robots, collaborative micro-robots, driverless cars, integration with digital twins and metaverse technologies

Why do we use robots?

- For tasks that humans avoid (dull, dirty, dangerous, difficult)
- Cost reduction
- Increase in productivity
- Improvement of quality

Typical applications of industrial robots

Production

- Materials management
  - Loading/unloading, packaging, palletizing
- Assembly
- Spraying/painting
- Electro-welding
- Cutting
- Polishing/finishing
- Mechanical processing
- Inspection
- Transportation

Warehouse

- Storage and retrieval of goods
  - Loading/unloading, packaging, palletizing
- Transportation
- Picking and placing
- Inspection

How to choose a robot

- Application
  - Feasibility
  - Economic
- Choose of a specific model of a robot

Example

Selection criteria for robots by General Electric

- The ongoing operation is simple and repetitive
- The maximum cycle time exceeds 5 seconds
- The assembly parts can be placed in an orderly manner and not randomly
- The parts have limited weight
- No inspection is required during the execution of the task
- It substitutes at least one person within 24 working hours

Comparison between robots

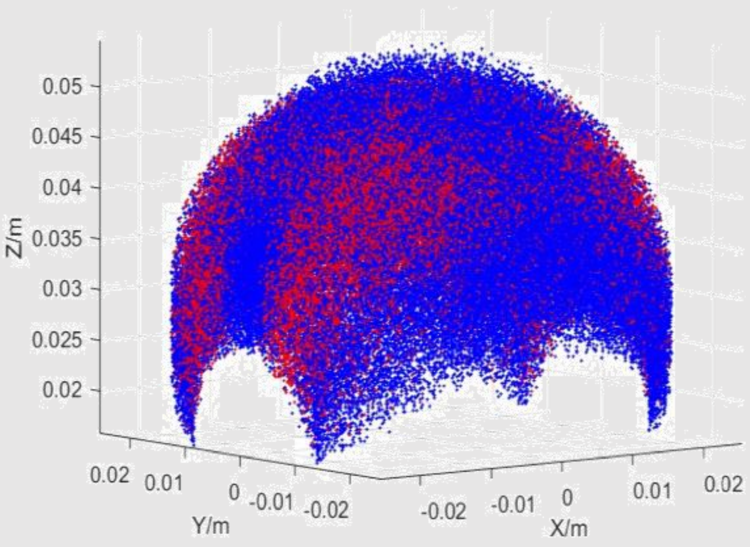
- Workspace and points of singularity
- Payload
- Speed
- Accuracy
- Repeatability
- Resolution
- Interfacing
- Work environment

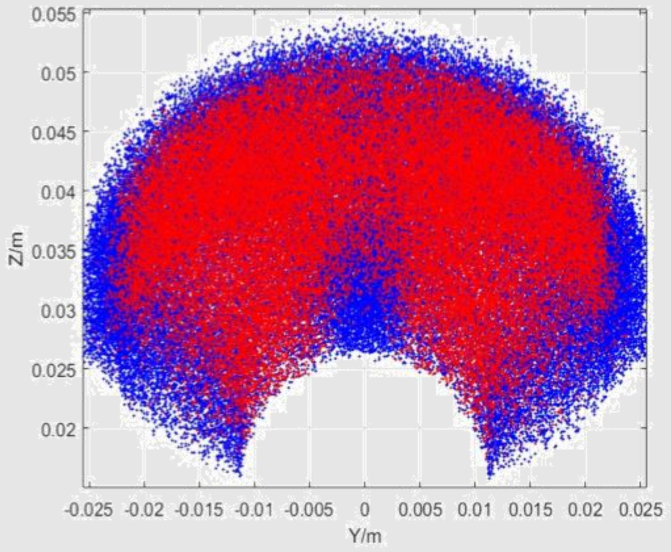
Workspace

The space accessible by the operator in any configuration. It depends on the geometric configuration of the operator, the size of the links, and the limits of joint movement. In some cases, the workspace refers to the subset of accessible points, specifically referring to the set of points that the operator can approach while maintaining the ability for arbitrary orientation at those points (dexterous workspace).

Workspace

- Workspace: The space accessible from the end-effector.
- Dexterous workspace: The space accessible from the end-effector in any orientation.
- Reachable workspace: The space where the robot can access in at least one orientation.

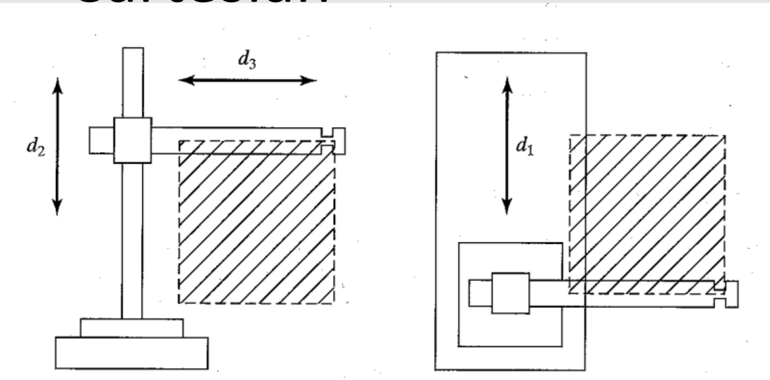


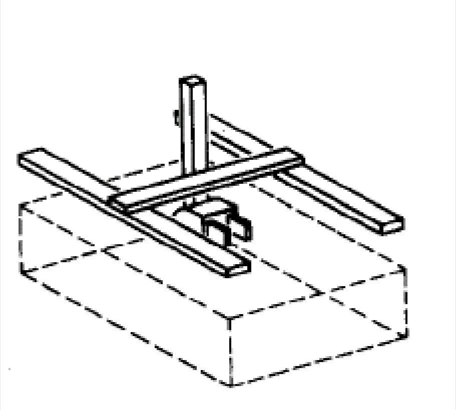


Zhi et al. “Kinematic Parameter Optimization of a Miniaturized Surgical Instrument Based on Dexterous Workspace Determination”

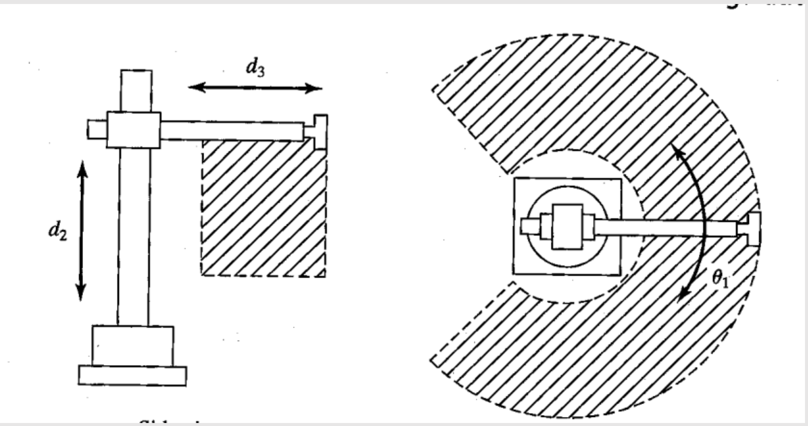
Workspaces

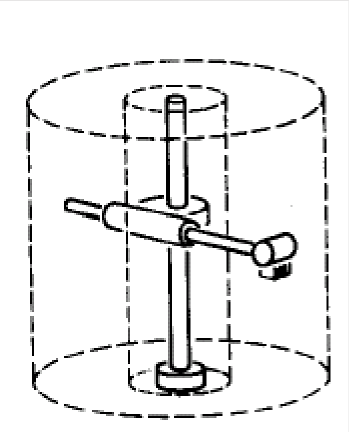
- Cartesian





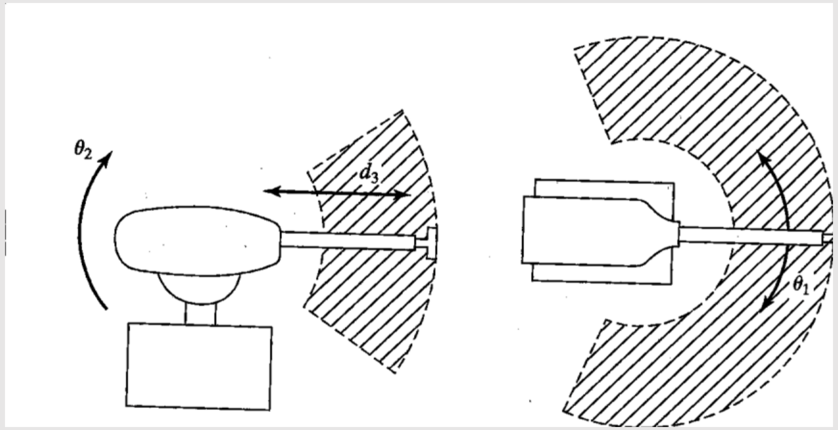
- Cylindrical

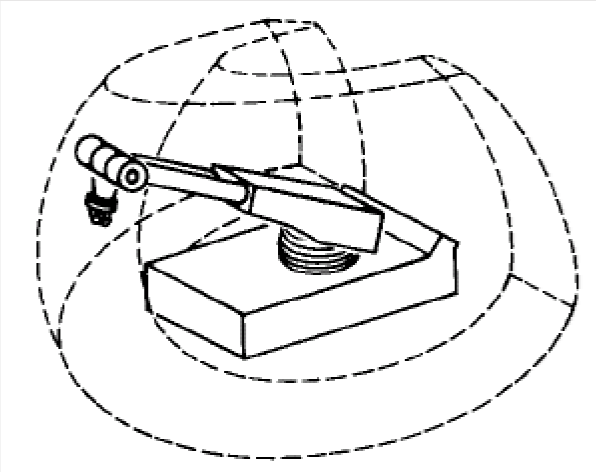




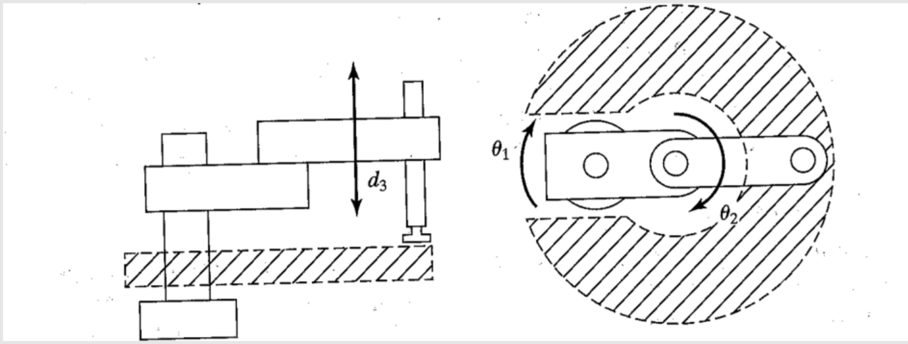
Workspaces

- Spherical



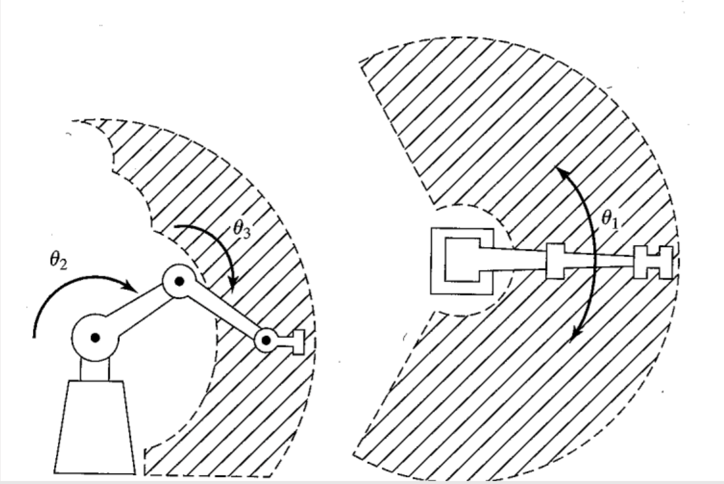


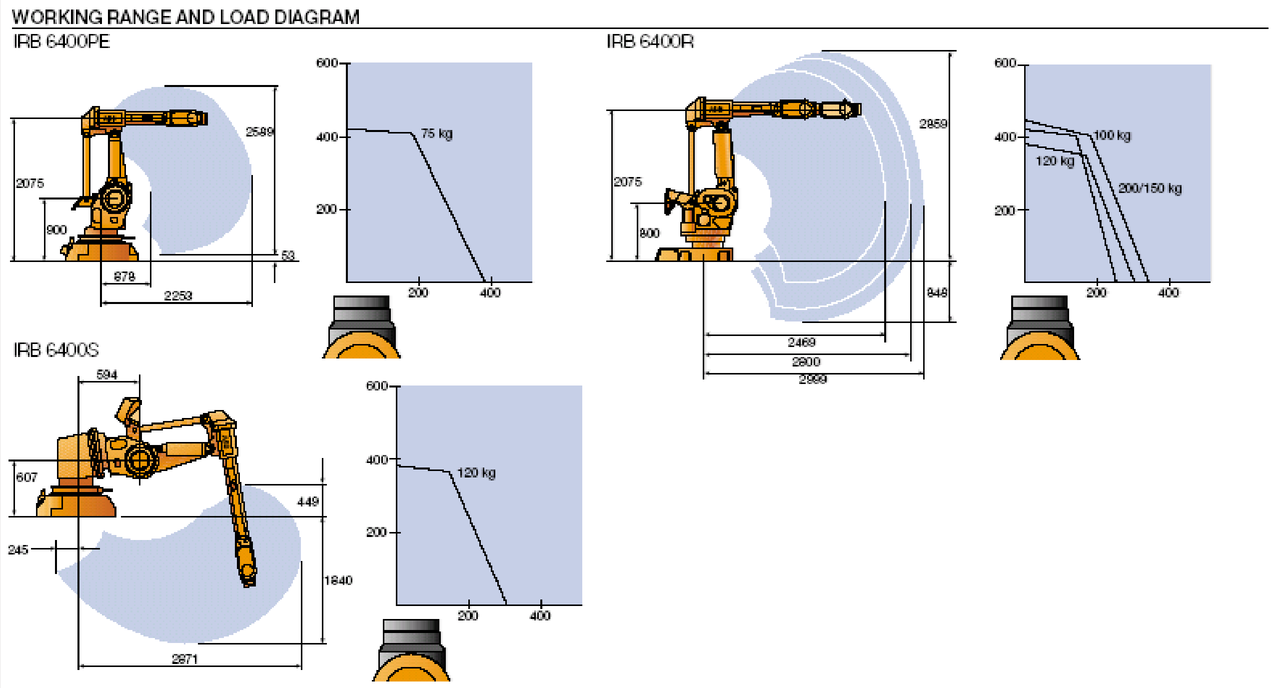
- SCARA



Workspaces

- Anthropomorphic





Efficiency of design resp. workspace

- Total combined length

$$L = \sum_{i=1}^{N} \left(a_{i-1} + d_i \right)$$

- Index of structural length

$$Q_L = L \big/ \sqrt[3]{w}$$

  (w is the volume of the workspce)

- The well-designed manipulators exhibit small L and low Q_L

Singularities

- The points at which a manipulator loses one or more degrees of freedom are called singularities

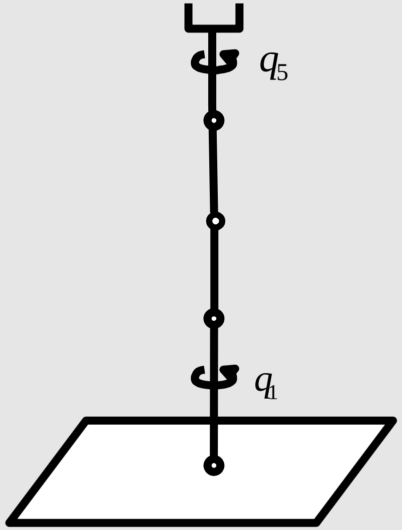
- All manipulators exhibit singularities at the boundaries of their workspace, while for many, there is a geometric locus of singularities within the workspace

- A configuration that results in a singularity is called a singular configuration

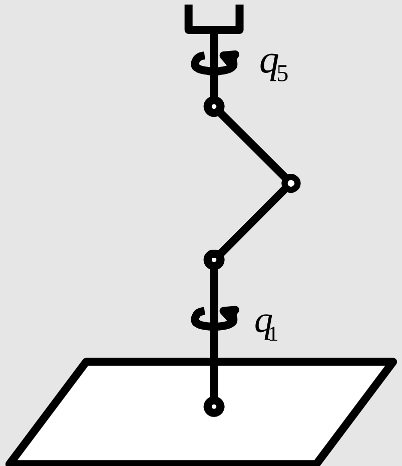
- A singular configuration can be avoided with some redundant degrees of freedom

Singularities

1. Boundary workspace singularities occur when the manipulator is fully extended or fully folded, so that the end-effector is close to the boundaries of the workspace.



2. Internal workspace singularities occur away from the boundaries of the workspace, usually when two or more joint axes align.



Manipulation capability

- Measure of manipulation capability

$$w = \sqrt{\left| det\left(J(q)J^T(q)\right) \right|}$$

or

$$w = \left| det\ J(q) \right|$$

- for non redundant manipulators
- A good manipulator possesses a high *w* in a broad portion of its workspace

Payload

- Payload
  - The maximum total load, consisting of the grab and the transported load, which the operator is able to carry without disturbances during transportation,
  - It depends on the size of the operator's structural elements, the transmission system, and the power of the actuators.

Velocity

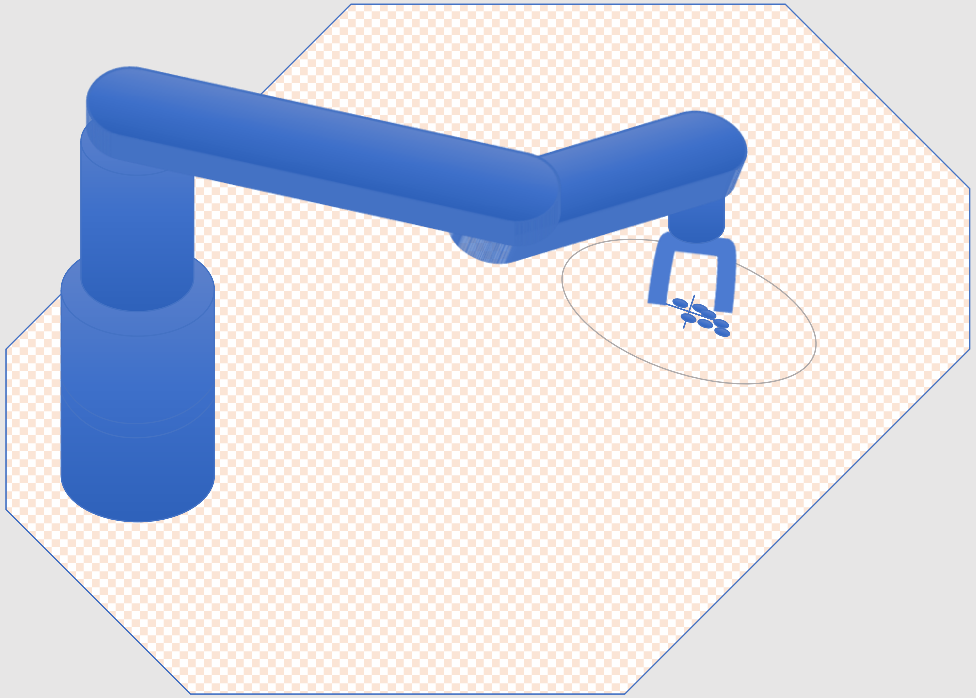
- It is apparent that the faster an operator is, the more work he can perform in a specific time frame and therefore, he is more efficient

Accuracy and repeatability

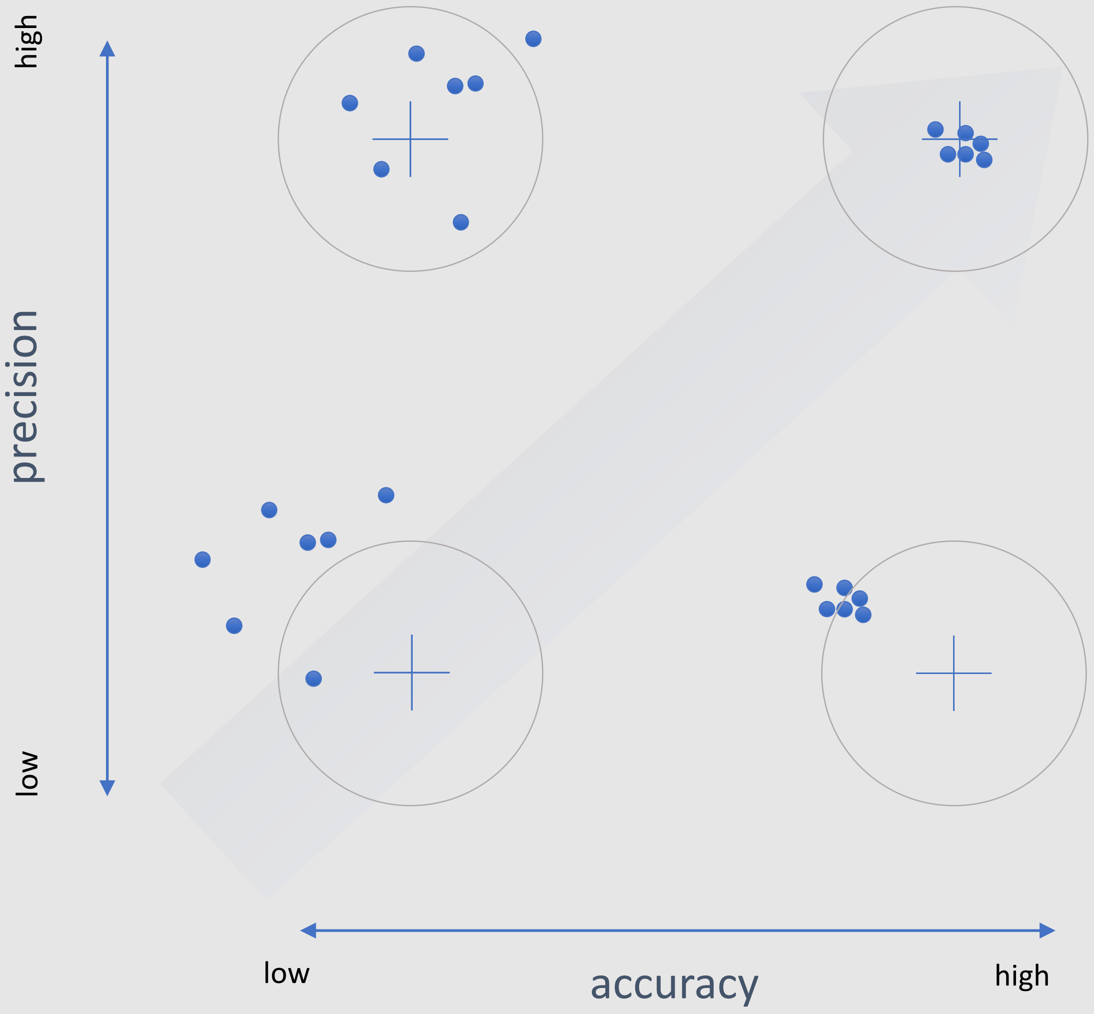
- Accuracy and repeatability
  - Accuracy is the ability to access a point in the workspace with the minimum possible error
  - Repeatability is the ability to access the same point during the repetition of the same movements.
- These parameters are uniquely defined with reference to the most adverse operating conditions
  - Of these two measures, repeatability is more important, as errors in precision can be corrected during the operator's programming phase when identified
- The exactness with which the operator can reach a computed point is the accuracy of the operator. Accuracy is limited by repeatability

Precision and repeatability

- Many industrial robots move to targets they have been taught.
- The operator is naturally transferred to the **taught point**, and the joint values are read by sensors and stored.
- In this case, the problem of inverse kinematics never arises since the target point is not specified by Cartesian coordinates but only in the space of actuators and joints.
- **Repeatability** is defined by the **precision** with which the operator returns to the taught point.
- The points that the operator can reach without being taught are called computed points.

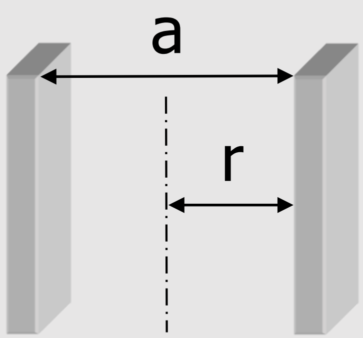


Accuracy vs Precision



Resolution

- Resolution
  - The width r of the minimum executable displacement
  - Particularly useful measure for precision manoeuvres, such as assembly or welding of various parts.
  - The analysis is linked to accuracy (a) as:
    - a=2*r



Interface

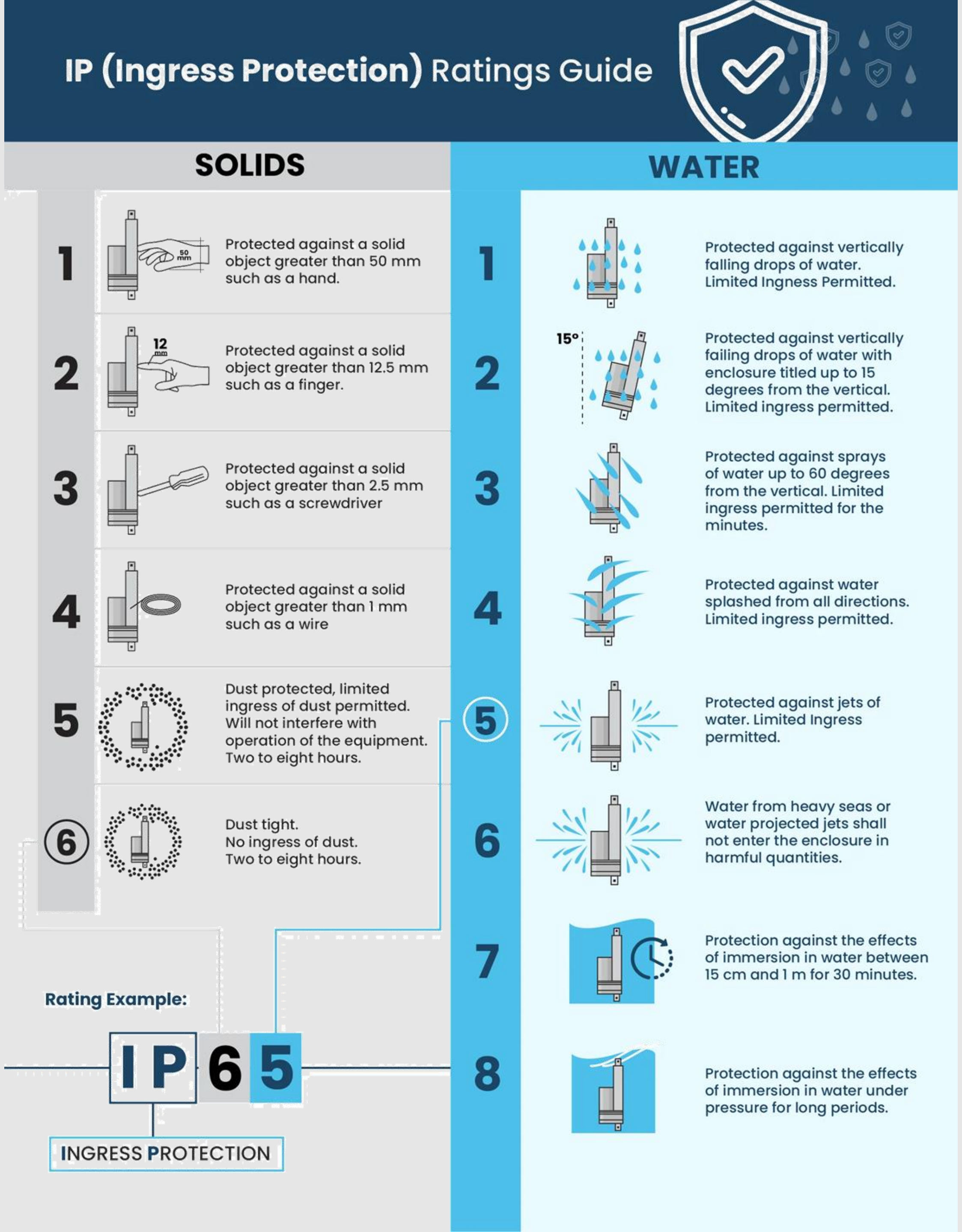
The interface of the robot includes the electrical connections of both the operator and the controller, as well as the ability to connect them to other industrial standards (CAN, Fieldbus, etc)

Working environment

- An important criterion for selecting a robotic system is the environment in which it will perform its operations
- Industrial environments are challenging environments, with temperatures often higher than normal, high humidity, noise, radiation, etc

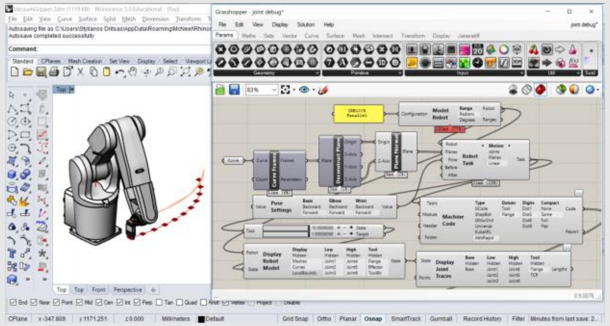
Working environment

- **IP** stands for 'Ingress Protection'. The IP number is used to define the protection of electronic devices enclosed in the robot against environmental factors
- These assessments are determined by specific tests. The IP number consists of two digits: the first refers to protection against solid objects and the second against liquids. The higher this number (up to 68), the better the protection of the robot


IP (Ingress Protection) Ratings Guide
SOLIDS
WATER
1
50 mm
Protected against a solid object greater than 50 mm such as a hand.
2
12 mm
Protected against a solid object greater than 12.5 mm such as a finger.
3
Protected against a solid object greater than 2.5 mm such as a screwdriver
4
Protected against a solid object greater than 1 mm such as a wire
5
Dust protected, limited ingress of dust permitted. Will not interfere with operation of the equipment. Two to eight hours.
6
Dust tight. No ingress of dust. Two to eight hours.
1
Protected against vertically falling drops of water. Limited Ingness Permitted.
2
15°
Protected against vertically failing drops of water with enclosure titled up to 15 degrees from the vertical. Limited ingress permitted.
3
Protected against sprays of water up to 60 degrees from the vertical. Limited ingress permitted for the minutes.
4
Protected against water splashed from all directions. Limited ingress permitted.
5
Protected against jets of water. Limited Ingress permitted.
6
Water from heavy seas or water projected jets shall not enter the enclosure in harmful quantities.
7
Protection against the effects of immersion in water between 15 cm and 1 m for 30 minutes.
8
Protection against the effects of immersion in water under pressure for long periods.
Rating Example:
IP65
INGRESS PROTECTION

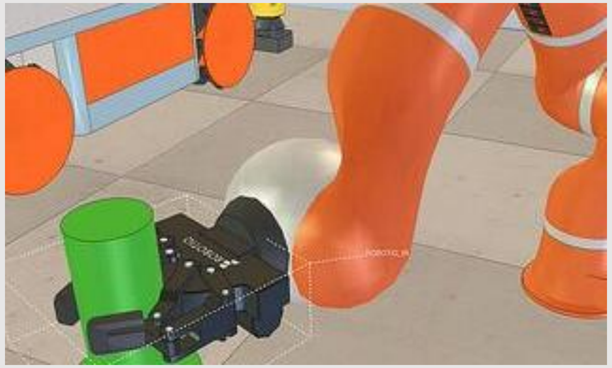
Programming

- Programming languages

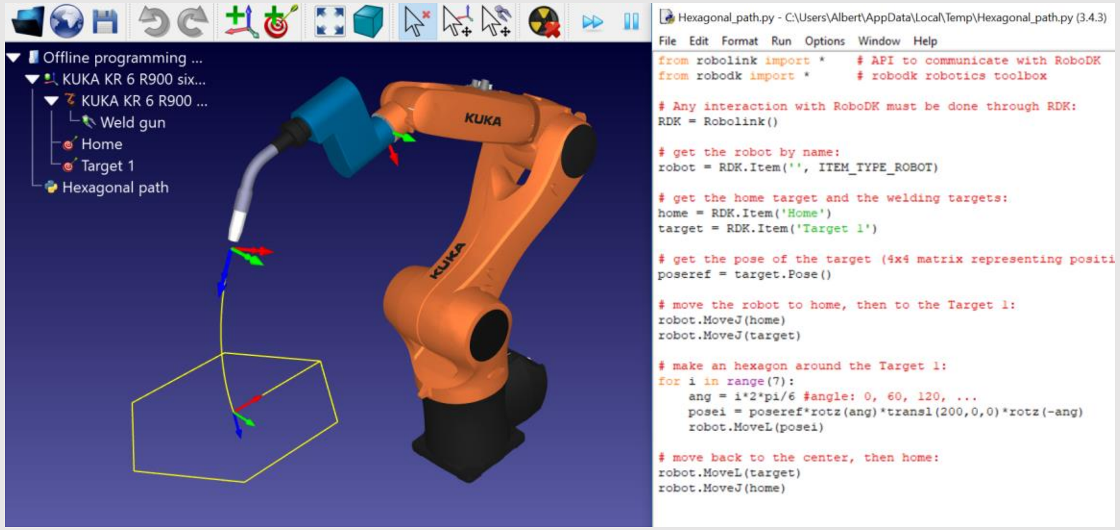


- Teaching by demanstration

- Simulation/off-line programming



Programming languages

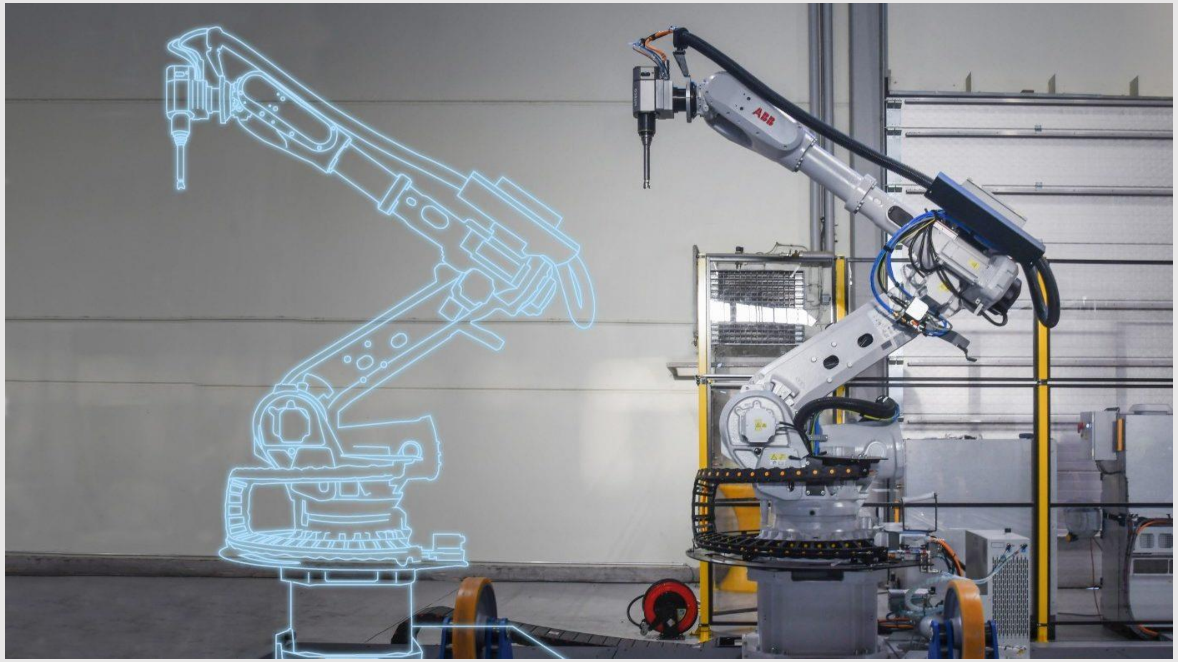


- More or less, all industrial robot manufacturers have developed their own programming language or have adapted well-known languages (C, Python, etc.) for their robots or have developed special libraries for these languages. For easy programming, the programming languages created by companies are usually graphical.
- This allows users to quickly create robot application programs without the need for specialized training. Such software use an open-source visual encoding method that presents the programming language or code as interlocking blocks. With the use of such a simplified approach, the user can program and use the robot without prior knowledge of any robot programming language.

Teaching by demonstration

- Teaching pendant: equipment connected to the robot controller, which transmits user commands to the robot, either in the joint space or in the Cartesian space. The points through which the robot passes can be memorized and the trajectories can be calculated.
- Other teaching methods by demonstration (e.g. Kinetiq) offer an intuitive addition to the teaching pendant. These methods include moving the robot, either by manipulating a force sensor or a controller attached to the robot's wrist just above the end-effector. Like with end-effector teaching, the operator stores each position in the robot’s control computer. Many collaborative robots have incorporated this programming method into their controllers, as it is easy for operators to immediately start using the robot with their applications.

Simulation/offline programming



- It involves the use of sophisticated simulation systems, allowing for robot simulation under operational conditions. Such tools, besides aiding in the design phase, also provide automatic program generation functions for robot control operations.
- It is more commonly used in research to ensure that advanced control algorithms function correctly before their implementation on a robot. However, it is also used in industry to reduce downtime and improve efficiency, through digital tweens. By leveraging digital twins alongside simulation and offline programming, engineers can create highly accurate virtual models that mimic real-world robot behaviour and conditions. This integration enables predictive analysis, real-time monitoring, and optimization, thereby improving both the design and operational phases of robotic systems across various industries.
- Simulation and offline programming can be particularly useful for batch production, as robots are more likely to be reconfigured multiple times than in mass production environments.
- Programming with simulation allows the robot to be programmed using a virtual prototype and workbench. If the simulation software is user-friendly, this can be a quick way for the user to test an idea before implementing it on the robot.

The next day

- Colaborative robots
- Artificial intelligence and machine learning
- Industrial metaverse
- Internet of things and digital twins

Collaborative robots

- **Collaborative robots (Cobots)** working alongside humans at close proximity in the factory, complementing each other's work.
  - Additional tasks
  - Repetitive tasks (robots)
  - Skill/inspiration (human)
- Progress in safety is required.
  - Currently laser grid
  - Use of multiple sensors (vision, artificial skin, sonar, etc.)

Artificial intelligence and machine learning

- Integration of **Artificial Intelligence and Machine Learning** into industrial robots for enhanced automation, adaptability, and decision-making capabilities

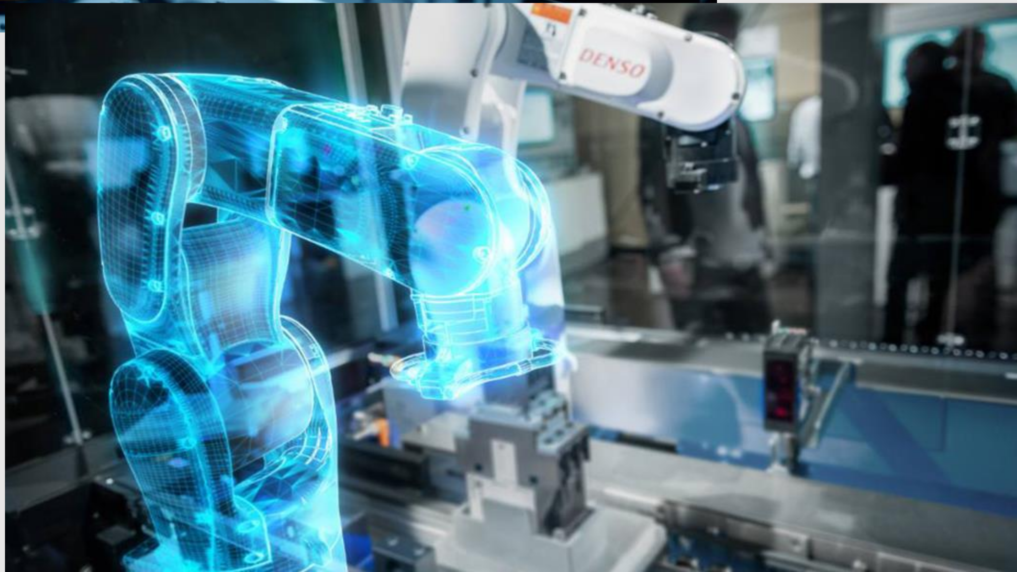
Industrial metaverse

- Virtual Robot Programming and Simulation: Utilize the industrial metaverse for programming and simulating robotic systems in a virtual environment before real-world deployment, enabling efficient testing and refinement of robot operations.

- Remote Operation and Monitoring: Leverage the industrial metaverse for remote control, monitoring, and maintenance of robotic systems across diverse locations, enhancing operational efficiency and reducing downtime.

Internet of things and digital twins

- Increasing connectivity and communication capabilities within robotic systems through IoT technologies, enabling remote monitoring and data-driven optimization
- Implementation of digital twin technology for virtual simulation, testing, and optimization of robotic systems, leading to improved performance, efficiency, and reliability



Ερωτήσεις

The next day

- **Big data** is a popular term used to describe the exponential growth and availability of data, both structured and unstructured.
  - Transaction data, sensors, machine-to-machine
  - Unstructured text documents, emails, videos, audio, stock data, and financial transactions