Industrial automation, communication and data management

Industrial robotics

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What is a robot?

A reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks.

(Robot Institute of America, 1980)
A robot is not just mechanics

Mechanics

Intelligence

Source: Comau Robotics
The manipulator consists of a series of rigid bodies (links) connected by joints.

One end of this chain makes the BASE, usually fixed to the floor.

At the other end we have the END EFFECTOR, where the gripper or tool is mounted.

Usually manipulators have six links:
- the first three make the positioning
- the last three (WRIST) make the orientation
Why six joints?

Source: Comau Robotics
Robots in action

https://www.youtube.com/watch?v=EbBwxDtDjPw
Robots in action

https://www.youtube.com/watch?v=VpwkT2zV9H0
Robots in the automation systems

**Rigid automation**
- The sequence of operations is fixed
- Production process composed of a sequence of simple operations
- Large production with very small variations

**Programmable automation**
- The sequence of operations can be changed
- Medium-low production batches
- Between batches the production plant has to be reconfigured

**Flexible automation**
- Production can be varied without idle times for conversion
- Machine characterized by high flexibility and configurability
  (FMS: Flexible Manufacturing Systems)
How many robots are sold by year?

Estimated annual worldwide supply of industrial robots
2009-2017 and 2018*-2021*

- 2009: 60,000
- 2010: 121,000
- 2011: 166,000
- 2012: 159,000
- 2013: 178,000
- 2014: 221,000
- 2015: 254,000
- 2016: 294,000
- 2017: 381,000
- 2018*: 421,000
- 2019*: 484,000
- 2020*: 553,000
- 2021*: 630,000

+14% on average per year

*forecast

Source: IFR World Robotics 2018
Where are robots sold?

Estimated worldwide annual supply of industrial robots 2016-2017 and forecast for 2018*-2021*

<table>
<thead>
<tr>
<th>Year</th>
<th>Asia/Australia</th>
<th>Europe</th>
<th>America</th>
<th>Source: IFR World Robotics 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>191,000</td>
<td>56,000</td>
<td>41,000</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>262,000</td>
<td>66,000</td>
<td>46,000</td>
<td></td>
</tr>
<tr>
<td>2018*</td>
<td>298,000</td>
<td>71,000</td>
<td>44,000</td>
<td></td>
</tr>
<tr>
<td>2019*</td>
<td>351,000</td>
<td>75,000</td>
<td>49,000</td>
<td></td>
</tr>
<tr>
<td>2020*</td>
<td>405,000</td>
<td>83,000</td>
<td>56,000</td>
<td></td>
</tr>
<tr>
<td>2021*</td>
<td>463,000</td>
<td>94,000</td>
<td>64,000</td>
<td></td>
</tr>
</tbody>
</table>

*forecast
In which countries are robots sold?

Estimated worldwide annual supply of industrial robots
15 largest markets 2017

- China: 137,900 units
- Japan: 45,600 units
- Rep. of Korea: 39,700 units
- United States: 33,200 units
- Germany: 21,400 units
- Taiwan: 10,900 units
- Vietnam: 8,300 units
- Italy: 7,700 units
- Mexico: 6,300 units
- France: 4,900 units
- Singapore: 4,500 units
- Spain: 4,200 units
- Canada: 4,000 units
- India: 3,400 units
- Thailand: 3,400 units

Source: IFR World Robotics 2018
What industrial robots are used for?

Estimated annual supply of industrial robots at year-end by industries worldwide 2015-2017

- **Automotive**: 2017: 126, 2016: 103, 2015: 98, +22%
- **Electrical/electronics**: 2017: 121, 2016: 91, 2015: 65, +33%
- **Metal**: 2017: 45, 2016: 29, 2015: 29, +55%
- **Plastic and chemical products**: 2017: 21, 2016: 20, 2015: 10, +9%
- **Food and beverages**: 2017: 19, 2016: 15, 2015: 8, +19%
- **Unspecified**: 2017: 20, 2016: 25, 2015: 35

Source: IFR World Robotics 2018
How many robots are there?

Estimated worldwide operational stock of industrial robots 2016-2017 and forecast for 2018*-2021*

<table>
<thead>
<tr>
<th>Year</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1,021</td>
</tr>
<tr>
<td>2010</td>
<td>1,059</td>
</tr>
<tr>
<td>2011</td>
<td>1,153</td>
</tr>
<tr>
<td>2012</td>
<td>1,235</td>
</tr>
<tr>
<td>2013</td>
<td>1,332</td>
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<td>2014</td>
<td>1,472</td>
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<tr>
<td>2015</td>
<td>1,632</td>
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<td>2016</td>
<td>1,828</td>
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<td>2017</td>
<td>2,098</td>
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<td>2019*</td>
<td>2,778</td>
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<tr>
<td>2020*</td>
<td>3,218</td>
</tr>
<tr>
<td>2021*</td>
<td>3,788</td>
</tr>
</tbody>
</table>

*forecast

Source: IFR World Robotics 2018
Common robot configurations (1/2)

**Anthropomorphic**
- The typical structure of the robot manipulator
- Dexterous structure
- Mechanical rigidity is a function of configuration

**SCARA**
- All joints with vertical axes
- Very rigid to vertical loads, compliant to horizontal loads
Common robot configurations (2/2)

Delta
- Parallel kinematic structure
- Very fast and accurate
- Limited workspace

Cartesian
- All joints give linear motion
- Very rigid mechanically
Parallel kinematic machines: extremely fast

[Video](https://www.youtube.com/watch?v=ipuhpzElGs4)
Redundant arms

https://www.youtube.com/watch?v=sZYBC8Lrmdo
Dual arm robots

- EPSON dual-arm
- ABB YuMi
- KAWASAKI DUARO
- KAWADA HIRO
A famous dual arm robot
The same robot doing funny things

[YouTube video link]

https://www.youtube.com/watch?v=KWmTX9QotGk
Problems in robotics

Robotics presents several problems. We will mention only a few of them:

- Kinematics
- Motion planning
- Control
Robot kinematics is the study of the motion of the robot. Two problems are of interest:
The task the robot has to accomplish is usually expressed in terms of the TCP (Tool Center Point).

This point is normally defined as being somewhere on the tool.

The TCP can be expressed in different coordinate systems (Cartesian frames).
The base coordinate system is located on the base of the robot:

- **The origin** is situated at the intersection of axis 1 (axis of the first joint) and the base mounting surface.
- **The xy plane** is the same as the base mounting surface.
- **The x-axis** points forwards.
- **The y-axis** points to the left (from the perspective of the robot).
- **The z-axis** points upwards.

Source: ABB
Each joint allows for one (and only one) *degree of freedom* between two links. We call *joint variable* the coordinate associated to such degree of freedom, and then we introduce the vector of joint variables:

Schematic draws of the joints:

- **ROTATIONAL JOINTS**
- **PRISMATIC JOINTS**
The direct kinematics problem is:

find position and orientation of the TCP frame w.r.t. the base frame, as a function of the joint variables.
Direct kinematics:

Consider a two-link planar robot:

\[ p_x = a_1 x + a_2 x = a_1 \cos(\theta_1) + a_2 \cos(\theta_1 + \theta_2) \]

\[ p_y = a_1 y + a_2 y = a_1 \sin(\theta_1) + a_2 \sin(\theta_1 + \theta_2) \]
In the general case the direct kinematics computation is complicated.

We need to introduce several intermediate coordinate systems.

But there are **systematic ways** to solve it.
The inverse kinematics problem is:

find joint variables given position and orientation of the tool frame w.r.t. the base frame.
The problem may admit no solutions (if position and orientation do not belong to the workspace of the manipulator)

The analytical solution (in closed form) may not exist. In this case numerical techniques are used

Multiple or an infinite number of solutions might exist

In general the solution is found without a systematic procedure, rather relying on intuition in manipulating the equations.
Inverse kinematics for a 2 d.o.f. planar manipulator

\[ p_x = a_1x + a_2x = a_1 \cos(\theta_1) + a_2 \cos(\theta_1 + \theta_2) \]
\[ p_y = a_1y + a_2y = a_1 \sin(\theta_1) + a_2 \sin(\theta_1 + \theta_2) \]

Squaring and summing:
\[ c_2 = \frac{p_x^2 + p_y^2 - a_1^2 - a_2^2}{2a_1a_2} \implies \theta_2 = \text{Atan}2(s_2, c_2) \]
\[ s_2 = \pm \sqrt{1 - c_2^2} \]

2 solutions

\[ c_1 = \frac{(a_1 + a_2c_2)p_x + a_2s_2p_y}{p_x^2 + p_y^2} \]
\[ s_1 = \frac{(a_1 + a_2c_2)p_y - a_2s_2p_x}{p_x^2 + p_y^2} \implies \theta_1 = \text{Atan}2(s_1, c_1) \]
Four admissible configurations exist:

- Right shoulder, upper elbow
- Left shoulder, upper elbow
- Right shoulder, lower elbow
- Left shoulder, lower elbow

If a spherical wrist is mounted, eight solutions of the inverse kinematics exist, that can be expressed in closed form.
Singularities are particular configurations of the robot, related to its mechanical design, where the same robot position (position and orientation of the tool frame) can be obtained with an infinite number of joint configurations.

At a kinematic singularity we have:

1. Loss of mobility (it is not possible to impose arbitrary motion laws)
2. Infinite solutions to the kinematic inversion problem
3. High velocities in joint space (around the singularity)

The singularities may happen:

1. At the borders of the manipulator work-space
2. Inside the manipulator work-space
What happens in a singularity?

- During joint interpolation, problems do not occur when the robot passes singular points.
- When executing a linear or circular path close to a singularity, the velocities in some joints may be very high.
- The robot configuration changes dramatically when the robot passes close to a singularity with linear or circular interpolation.

Singularities are dangerous!

https://www.youtube.com/watch?v=zLGCurgsqg8
The generation of the motion of the robot means that we need to decide how the robot has to move: what points in space should it cover? and how fast?
A general scheme for the robot controller

A robot controller is composed of several functional units:
Joint space

Trajectories in **joint space**: the desired joint positions are directly specified

- singularities do not create problems
- it is a mode of interest when we just want that the axes move from an initial to a final pose (and we are not interested in the resulting motion of the end effector)
- online kinematic inversion is not needed
For each joint variable it is defined how it evolves from an initial value to a final one in a finite time. Several methods exist (polynomial, harmonic, cycloidal functions, trapezoidal velocity profiles, ...).
Operational space

Trajectories in the operational space: the path (position and orientation) of the robot end effector is specified in the common Cartesian space.

- task description is natural
- constraints on the path can be accounted for
- singularities generate problems
- online kinematic inversion is needed

Trajectory planning in the operational space entails both a path planning problem and a timing law planning problem.
Linear path

A linear path is completely characterized once two points in Cartesian space are given.

A motion along a segment in space corresponds to a **Move linear** in a motion programming language.
A circular path can be defined assigning three points in space belonging to the same plane:

A motion along a segment in space corresponds to a **Move circular** in a motion programming language.
A first mode for motion programming is the so called teaching-by-showing (also known as lead-through programming).

Using the teach-pendant, the operator moves the manipulator along the desired path. Position transducers memorize the positions the robot has to reach, which will be then jointed by a software for trajectory generation, possibly using some of the intermediate points as via points with over fly motions. The robot will be then able to autonomously repeat the motion.

No particular programming skills are required to the operator, who might well be a workshop technician.
A more flexible solution is to program the robot using a programming language.

A **robotic programming language** is a high level language the operator can use in order to program the motion of the robot as well as complex operations where the robot, inside a work-cell, interacts with other machines and devices. With respect to a general purpose programming language, the language provides specific robot oriented functionalities.

In the following we will show an example of a program written in the PDL2 programming language by COMAU Robotics.
The program moves pieces from a feeder to a table or to a discard bin, depending on digital input signals:

```plaintext
PROGRAM pack
VAR
    home, feeder, table, discard : POSITION
BEGIN CYCLE
    MOVE TO home
    OPEN HAND 1
    WAIT FOR $DIN[1] = ON
    -- signals feeder ready
    MOVE TO feeder
    CLOSE HAND 1
    IF $DIN[2] = OFF THEN
        -- determines if good part
        MOVE TO table
    ELSE
        MOVE TO discard
    ENDIF
    OPEN HAND 1
    -- drop part on table or in bin
END pack
```

1. Feeder
2. Robot
3. Discard Bin
4. Table
Motion control of a robot is performed with feedback controllers:
When is a motion control “good”?

When it makes the robot both accurate and repeatable...

- Poor accuracy, poor repeatability
- Poor accuracy, good repeatability
- Good accuracy, poor repeatability
- Good accuracy, good repeatability

Source: Alessandro De Luca
When is a motion control “good”?

... and when it is fast...

https://www.youtube.com/watch?v=5ndaQwn15ng
Controlling the interaction

To control the interaction with the environment we need sensors

- Force sensors
- Vision sensors (cameras)
Control with force sensors
Control with vision