CHAPTER 5

INDUSTRIAL ROBOTICS

5.1 Basic of Robotics

5.1.1 Introduction

There are two widely used definitions of industrial robots:

i) An industrial robot is a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or special devices through variable programmed motions for the performance of a variety of tasks (By RIA : Robotics Institute of America)

ii) An industrial robot is a general-purpose, programmable machine possessing certain anthropomorphic characteristics (By Mikell Groover – a more general definition)

The first industrial robot is introduced by Unimation Inc. USA in 1952. It is 10 years after the first numerical control (NC) machine tool was introduced by Massachuset Institute of Technology (MIT) USA.

5.1.2 Robotics Technology

Robotics Technology is referred to a technology used to design and develop an industrial robot to do work or perform the required tasks which previously done by humans. The technology in general comprises of mechanical, electrical, electronic, and computer. In term of control, industrial robots used the same technology as CNC machine. It is numerical control technology: a control make use of numerical number/binary digit (1,0).

Reasons for commercial and technological importance of industrial robots are as follows:

1. Robots can be substituted for humans in hazardous working environment.
2. Robots can perform their work cycle consistently and repeatability that cannot be attained by humans.
3. Robots can be reprogrammed to perform various tasks.
4. Robots are controlled by computers and can therefore be connected to other computer controlled machines such as NC machines to achieve computer integrated manufacturing (CIM)
5.1.3 Structure of Industrial Robot Manipulator

The structure of industrial robot manipulator (or arm) is constructed/made of a series of joints and links as shown in Figure 5.1. The gripper or tool to handle a work piece is attached to the end-of-arm. Each joint is considered as a degree of freedom for a robot manipulator to move to a certain extent to do work. For example, if a robot has 2 joints, the robot has 2 degree of freedom. Therefore a robot with \( n \) joint has \( n \) degree of freedom.

![Figure 5.1 Links and Joints of Robot Manipulator](image1)

Basically there are 4 geometrical configurations or types of industrial robot as follows:

1. Cartesian  
2. Cylindrical  
3. Polar  
4. Jointed Arm or Articulated

Figure 5.2 shows the 4 geometrical configurations or types of industrial robot.

![Figure 5.2 Geometrical configurations or types of industrial robot](image2)
1. Cartesian Robot:
   - All axes move in linear direction
   - Usually driven by pneumatic / hydraulic cylinders
   - Good for pick and place operation

2. Cylindrical Robot:
   - Combination of linear and angular movements
   - Usually driven by electrical motors and pneumatic / hydraulic cylinders
   - Good for pick and place, spot welding and assembly operations.

3. Polar Robot:
   - Combination of linear and angular movements
   - Usually driven by electrical motors and pneumatic / hydraulic cylinders
   - Good for pick and place, spot welding, spraying and assembly operations.

4. Jointed Arm or Articulated
   - All axes move in angular direction
   - Usually driven by electrical motors
   - Good for pick and place operation, spot welding, arc welding, spraying, and assembly operation

5.1.4 Robot Motion Analysis: An Introduction to Manipulator Kinematics

Manipulator kinematics is concerned with the position and orientation of the robot’s end-of-arm or the end effector attached to it as a function of time but without regard for the effects of force or mass. Our treatment of manipulator kinematics will be limited to the mathematical representation of the position and orientation of the robot’s end-of-arm.

Consider two manipulators with two degrees-of-freedom: (a) an OO (orthogonal joint) robot and (b) an RR (rotational joint) robot as shown in Figure 5.3. The robot manipulator consists of a sequence of joints ($J_1, J_2$) and links ($L_1, L_2$). It is a 2 degrees-of-freedom of manipulator. If the manipulator has $n$ degrees-of-freedom the joints will be $J_1, ..., J_n$ and the links $L_1, ..., L_n$.

![Figure 5.3 Two manipulators with two degrees-of-freedom: (a) an OO robot and (b) an RR robot.](image-url)
The values of the positions of the joints relative to their respective inputs links as shown in Figure 5.3(a) are $\lambda_1$ and $\lambda_2$. In Figure 5.3(b) the values are $\theta_1$ and $\theta_2$.

The positions and orientation of the joints in Figures 5.3(a) and (b) are identified as follows:

$$P_j = (\lambda_1, \lambda_2)$$

$$P_j = (\theta_1, \theta_2)$$

An alternative way to represent position is by Cartesian or World Coordinate. The end-of-arm position $P_w$ is defined in Cartesian or World Coordinate as:

$$P_w = (x, z)$$

For a robot with six joints:

$$P_w = (x, y, z, a, b, c)$$

The positions of $x$, $y$, $z$, $a$, $b$, $c$ are in distance unit (in, mm, etc)

### 5.1.4.1 Forward and Backward Transformation for a Robot with Two Joints

Both the joint space and world space methods of defining position in the robot’s space are important. Mapping from joint space to world space is called **forward transformation** and converting from world space to joint space is called **backward transformation**.

The forward and backward transformations are readily accomplished for the Cartesian coordinate robot of Figure 5.3 because the $x$ and $z$ coordinates correspond directly with the values of the joints.

For forward transformation:

$$x = \lambda_2$$

$$z = \lambda_1$$

(5.5)

For backward transformation:

$$\lambda_1 = z$$

$$\lambda_2 = x$$

(5.6)

Where $x$ and $z$ are the coordinate values in world space and $\lambda_1$ and $\lambda_2$ are the values in joint space. For the RR robot of Figure 5.3 (b), the forward transformation is calculated by noting that the lengths and directions of the two links might be viewed as vectors in space:

$$\mathbf{r}_1 = \{L_1 \cos \theta_1, L_1 \sin \theta_2\}$$

(5.7a)

$$\mathbf{r}_2 = \{L_2 \cos (\theta_1 + \theta_2), L_2 \sin (\theta_1 + \theta_2)\}$$

(5.7b)

Vector addition of $\mathbf{r}_1$ and $\mathbf{r}_2$ (and taking account of link $L_0$) yields the coordinate values of $x$ and $y$ at the end-of-arm:

$$x = L_1 \cos \theta_1 + L_2 \cos (\theta_1 + \theta_2)$$

(5.8a)

$$z = L_0 + L_1 \sin \theta_1 + L_2 \sin (\theta_1 + \theta_2)$$

(5.8b)
For the RR robot, we must first decide whether the robot will be positioned at the $x, z$ coordinates using an “above” or “below” configuration as defined in Figure 5.4.

![Figure 5.4](image)

**Figure 5.4** For most $x$-$z$ coordinates in the RR Robot’s work volume, two alternative pairs of joint values are possible, called “above” and “below”.

Given the link values $L_1$ and $L_2$, the following equations can be derived for the two angles $\theta_1$ and $\theta_2$:

\[
\cos \theta_2 = \frac{x^2 + (z - L_0)^2 - L_1^2 - L_2^2}{2L_1L_2} \quad (5.9a)
\]

\[
\tan \theta_1 = \frac{\{(z - L_0)(L_1 + L_2 \cos \theta_2) - xL_2 \sin \theta_2\}}{\{x(L_1 + L_2 \cos \theta_2) + (z - L_0)L_2 \sin \theta_2\}} \quad (5.9b)
\]

### 5.1.4.2 Forward and Backward Transformation for a Robot with Three Joints

For the forward transformation, we can compute the $x$ and $z$ coordinates in a way similar to that used for the previous RR robot. From Figure 5.5 the values of $x$ and $z$ can be computed as follows:

\[
x = L_1 \cos \theta_1 + L_2 \cos (\theta_1 + \theta_2) + L_3 \cos (\theta_1 + \theta_2 + \theta_3) \quad (5.10a)
\]

\[
z = L_1 \sin \theta_1 + L_2 \sin (\theta_1 + \theta_2) + L_3 \sin (\theta_1 + \theta_2 + \theta_3) \quad (5.10b)
\]

The angle made by the wrist with the horizontal:

\[
\alpha = \theta_1 + \theta_2 + \theta_3 \quad (5.10c)
\]
The coordinates of joint 3 \((J_3)\) are:

\[
x_3 = x - L_3 \cos \alpha
\]

\[
z_3 = z - L_3 \sin \alpha.
\]

Knowing the coordinates of joint 3, the problem of determining \(\theta_1 + \theta_2\) is the same as for the previous RR configuration robot.

\[
\cos \theta_2 = \frac{x_3^2 + z_3^2 - L_1^2 - L_2^2}{2L_1L_2}
\]

\[
\tan \theta_1 = \frac{z_3(L_1 + L_2 \cos \theta_2) - x_3L_2 \sin \theta_2}{x_3(L_1 + L_2 \cos \theta_2) + z_3L_2 \sin \theta_2}
\]

The values of joint 3 is then determined as:

\[
\theta_3 = \alpha - (\theta_1 + \theta_2)
\]

**EXAMPLE 5.1 Backward Transformation for a RR:R Robot**

Given the world coordinates for a RR:R robot (similar to that in Figure 5.5) as \(x = 300\) mm, \(z = 400\) mm, and \(\alpha = 30^\circ\); and given that the links have values \(L_1 = 350\) mm, \(L_2 = 250\) mm, and \(L_3 = 50\) mm, determine the joint angles \(\theta_1\), \(\theta_2\), and \(\theta_3\).

**Solution:** The first step is to find \(x_3\) and \(z_3\) using Eqs. (5.11) and the given coordinates \(x = 300\) and \(z = 400\).

\[
x_3 = 300 - 50 \cos 30 = 256.7 \text{ mm}
\]

\[
z_3 = 400 - 50 \sin 30 = 375 \text{ mm}
\]

Next, we find \(\theta_2\) using Eq. (5.12a):

\[
\cos \theta_2 = \frac{256.7^2 + 375^2 - 350^2 - 250^2}{2(350)(250)} = 0.123 \quad \theta_2 = 82.9^\circ
\]

The angle \(\theta_1\) is found using Eq. (5.12b):

\[
\tan \theta_1 = \frac{375(350 + 250 \cos 82.9^\circ) - 256.7(250) \sin 82.9^\circ}{256.7(350 + 250 \cos 82.9^\circ) + 375(250) \sin 82.9^\circ} = 0.4146 \quad \theta_1 = 22.5^\circ
\]

Finally, \(\theta_3 = 30^\circ - 82.9^\circ - 22.5^\circ = -75.4^\circ\)
5.2 Industrial Robot Application

5.2.1 Introduction

Industrial robots are designed and developed to perform various tasks in industries such as welding of product components, painting of products, pick and place of work pieces/components, assembly of components to produce products, inspection and packing of components/products etc.

5.2.2 Selection of Industrial Robots

There are several important specifications need to be considered when come to select industrial robots to do work/perform task as follows:

1. Payload

Payload is the maximum load (weight of component) can be handled by a robot at certain speed of movement while performing tasks (doing work). Industrial robots could have 1 kg/ 2 kg / 5 kg / 20 kg / 50 kg / 100 kg / 1000 kg, etc. payload.

2. Repeatability

Repeatability is the ability of robot to return to the same point again and again after that point has already been taught and recorded. For industrial robots, repeatability is a more important consideration than accuracy because the robot is usually taught with a teach pendant the first time. Repeatability could be 0.01 mm, 0.1 mm etc. deviation/error from the point. It depend a lot on the quality of the robots.

3. Speed

Speed is another characteristic that may disappoint some potential robot users. Pick-and-place cycles used in machine loading and unloading are typically rated at two to three seconds for small pneumatic axis-limit robots. Some of these robots can achieve one-second cycles, and cam-operated mechanical manipulators can be even faster. A typical speed for a large, servo-controlled, hydraulic robot is in the range of 50 in./sec (about 1.2 m/sec).

5.2.3 Justification of Industrial Robots

Industrial robots are effective at boring, repetitive jobs that require little or no intelligence or judgement. They are also good for extremely fatiguing, hot jobs or for jobs that must be performed in toxic or otherwise dangerous environment. Industrial robots can produce higher quality of products and the quality is consistent. This is very difficult to be achieved by humans.

In business, economic justification is also important. Robots range widely in cost from USD 5,000 (about RM 15,000) on the low end to over USD 150,000 (about RM 450,000) on the high end, using the early 1990s as a reference point. Now the cost is much lower due to advancement in computer technology and a lot of robots are used in industry. They are comparable in cost to many machine tools, except for the most expensive NC machine tools, which are higher.
Neither machine tools nor robots are difficult to justify when their roles are vital to the feasibility of the process. For instance, some form of robot may be essential when assembling radioactive components in a product.

### 5.2.4 Programming of Industrial Robots

Basically there are two methods of programming of industrial robots (giving instruction to robots to do work) : Teach pendant programming and Keyboard programming.

1. **Teach Pendant Programming**

Teach pendant or online programming is carried out using a teach pendant designed for the robot. Different brand of robot has different design of teach pendant. Figure 5.6 shows the teach pendant for FANUC robot. The robot is taught to perform the required task by using the pendant. Positions/points where the robot is moved to are recorded using pendant and stored in the computer. The stored positions will be used for writing computer program for robot to perform the task. This method is also referred as teach and play back. It is user friendly and easy to program. However it is not suitable to program a lot number of robots to work together in one cell/system because very tedious.

![Figure 5.6 FANUC Robot Teach Pendant](image)

2. **Keyboard Programming**

Keyboard programming or offline programming is carried out using computer as shown in Figure 5.7 with the robot simulation software provided by the robot manufacturer. The software is used to determine the positions/points where the robot is to be moved to perform the required task. The positions will be used for writing the robot program. This method of programming is good for a lot number of robots to work together in one cell/system.
Almost all industrial robots are programmed using robot programming languages which are
developed by the robot manufacturers using computer programming languages such as
BASIC, C, FORTRAN, PASCAL, etc. Different brands of industrial robots have different
name of programming languages such as VAL, ARMBASIC, AML etc. VAL and
ARMBASIC are developed using BASIC programming language whereas AML is using C.

Below is an example of a robot program written using VAL language. The program is used
to command/instruct a robot to pick up work pieces at location A and place them at location B.

<table>
<thead>
<tr>
<th>program</th>
<th>A.TO.B.</th>
<th>OPEN</th>
<th>MOVE A</th>
<th>CLOSEI</th>
<th>MOVE B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This is the program name.</td>
<td>Open the robot gripper jaws.</td>
<td>Move the robot gripper to defined position A.</td>
<td>Close the gripper jaws immediately.</td>
<td>Move the gripper to defined position B.</td>
</tr>
</tbody>
</table>
Example 5.2 : Application of industrial robot in pick and place task:
A robot is used to load and unload a CNC Kingsbury milling machine from a conveyor as shown in Figure 2.

![Figure 2 Loading and Unloading Machine by Robot](image)

The following average robot operation times apply:
- Pick up part from conveyor (including average wait time for part to arrive in pickup position): 3.0 sec
- Move robot hand from conveyor to machine: 2.0 sec
- Load part into machine and back away from machine so the machine can start: 1.2 sec
- Unload part from machine: 0.8 sec
- Move robot hand from machine to conveyor: 2.0 sec
- Deposit part onto conveyor: 0.4 sec

The CNC milling machine operation cycle requires 60 seconds. Assuming an average of 10 percent system downtime (90% efficiency) for maintenance, clearance of malfunctions, and other causes, find the daily 8-hour shift production rate.

**Answer:**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine operation cycle</td>
<td>60.0 sec</td>
</tr>
<tr>
<td>Unload machine</td>
<td>0.8 sec</td>
</tr>
<tr>
<td>Move to conveyor</td>
<td>2.0 sec</td>
</tr>
<tr>
<td>Deposit finished part on conveyor</td>
<td>0.4 sec</td>
</tr>
<tr>
<td>Pick up new part</td>
<td>3.0 sec</td>
</tr>
<tr>
<td>Move to machine</td>
<td>2.0 sec</td>
</tr>
<tr>
<td>Load into machine</td>
<td>1.2 sec</td>
</tr>
</tbody>
</table>

**Total time** 69.4 sec

**Production rate** = \( \frac{1 \text{ unit}}{69.4 \text{ sec}} \times 60 \text{ sec/min} \times 60 \text{ min/hr} \times 8 \text{ hr/shift} \times 0.9 \)

\[= 373.48 \text{ (373) units/shift} \]