Course Notes

for

Mechanical Engineering 4K03

Robotics

Term I, 2013/2014

1. INTRODUCTION

1.1 History

Figure 1.1 An automata.

1700s-1800s Creation of many clockwork mechanical "automata". These machines where capable of graceful movements including handwriting.

1801 Joseph Jacquard invents a textile machine which is operated by punch cards. The machine is called a programmable loom.

Before 1905 Most products were made by skilled craftsmen. The product cost was high. Termed "manual production".

1905 Ford Motor Company introduced the concept of "mass production" and the assembly line. This dramatically lowered the costs of manufactured products and made them affordable to the general population.

1922 Czech author Karel Capek's play introduced the word "Rabota" refering to a human-like machines used for warfare. The plot was later borrowed for the "Terminator" film.

1942 The word "robotics" first appears in the short story "Runaround" by Isaac Asimov. Asimov later introduced the idea of a "positronic brain" (used by the character "Data" in Star Trek).

1948 Invention of the transistor.

1950 W. Grey Walter produces the first mobile autonomous robots. Although very simple in design they are able to produce animal like behaviours.

1952 First numerically controlled (NC) machine was built at MIT.

1954 First programmable robot developed by George Devol.

1955 Denavit and Hartenburg developed homogeneous transformation matrices.

1961 U.S. patent issued to George Devol for "Programmed Article Transfer".

1962 Joe Engleberger forms Unimation, first industrial robots (based on Devol's patent) produced and sold to GM.

1968 First computer controlled mobile robot built at Stanford University.

1983 Robotics becomes a popular subject in industry and universities.

1996 Honda introduces its P2 humanoid robot. This robot can autonomously climb stairs but only has a battery life of 15 minutes. It took $80 million and a team of 30 Engineers 10 years to develop.

1999 Sony introduces "Aibo" a robotic dog capable of learning new behaviours.

Figure 1.2 A Sony Aibo meets a distant cousin.

2000 The “da Vinci Robotic Surgical System” is introduced. More than 1,000 systems have been sold to date, at a retail price of more than $1,000,000 each.

2001 Honda introduces “Asimo” a new version of their humanoid robot.

2002 iRobot launches their “Roomba” floor vacuuming robot. More than 5,000,000 have since been sold.

2008 Touch Bionics introduces their “i-LIMB Hand” prosthetic hand. The result of more than 20 years of research, it features touch sensors and sophisticated force control software that allows the user to grasp household objects with ease.

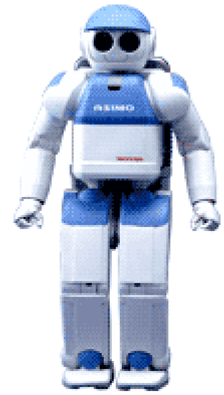


Figure 1.3 Asimo.

2009 Willow Garage demonstrates their “PR2” robot. This robot features open-source software and 3D vision; and is capable of autonomous behaviours such as navigating a hallway, opening doors and plugging itself into a standard electrical outlet.

1.2 Definitions of Basic Terms

Robot: Unfortunately this term has been used in several inconsistent ways. The most common definition is: a mechanical device with multiple degrees-of-freedom that performs the successive stages of a task according to a software program. This is the typical industrial situation. Others generalise this term to include machines that are manually operated using some type of joystick. This is often called “teleoperation” or “telerobotics”. Still others feel a true “robot” should be capable of autonomous behaviour.

Degrees-of-freedom: The number of degrees-of-freedom (DOF) that a robot possesses is the number of displacement variables (linear or angular) that must be specified to locate all parts of the robot. For a typical robot, the number of DOF equals the number of motor-driven joints.

Types of joints: The two most common types of joints are revolute joints and prismatic joints. Both have a single DOF. A revolute joint produces rotary motion while a prismatic joint produces linear motion.

Automation: The technique of making an apparatus, a process or a system operate by itself without human attention.

Hard Automation: Specialised machines for high-volume manufacturing usually in the form of an assembly line. Whenever the product is changed the machines must be shutdown and the hardware changed or “retooled”. Since periodic modification of the hardware is necessary this is termed “hard automation”. This approach is efficient for large production volumes.

Flexible Automation: Use of robots in place of the specialised machines used in hard automation. The robots may be reprogrammed when the product changes so minimal retooling is required. Most current automotive assembly lines are in fact a mix of hard and flexible automation. Also called “soft automation”.

Robotics: The study, design and development of “robotic systems”. Robotic systems consist of robots and other devices that are used together to form the desired task. Robotics is an interdisciplinary subject that benefits from mechanical engineering, electrical and computer engineering, computer science, biology and psychology.

Manipulator: A specific type of robot whose mechanical design is similar to a crane. It features motor-driven joints and links connected in series to a fixed base. Also known as a “robot arm” due to its arm-like structure.

Mobile robot: A robot capable of moving itself around in its environment (known as “self-locomotion”). Normally these are wheel driven but walking robots (humanoid, canine-like or insect-like) are also being developed. These robots use sophisticated sensors and computer programs to navigate themselves and to avoid avoid hitting obstacles. Mobile robots are more sophisticated than the automatic guided vehicles (AGVs) used in some factories. AGVs are mobile platforms for transporting goods and materials. Most AGVs use buried wires for guidance and have limited sensing or autonomous behaviour.

Actuators: Actuators provide the forces (or torques) required to move the DOF of the robot. In effect they are the “muscles” of the robot. Normally these consist of electric motors but pneumatic and hydraulic powered robots also exist.

Sensors: Sensors collect information about the internal state of the robot or about its environment. For example, to control the angle of the robot’s “elbow” joint it must first be measured by a suitable sensor.

Controller: The controller is responsible for controlling the motions of the robot. It consists of microprocessors and electronic hardware to receive signals from the robot’s sensors (and potentially other external sensors) and to send signals to the robot’s actuators. Typically there are four levels of software involved. At the top level is the operating system for the robot. At the second level is the user program written in the native language for the robot. At the third level is the software to convert the user program instructions into the desired motions for the robot’s joints using the kinematic equations for the robot. At the fourth level is the software for controlling the individual joint actuators.

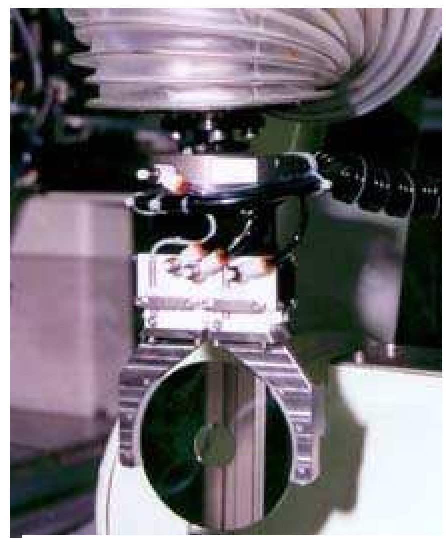


Figure 1.4 This gripper is one form of end-effector.

End-effector: The device intended for interacting with the environment. It is attached to the last joint of the robot and may be a simplified type of mechanical hand known as a “gripper” or some other tool like a welding gun or a painting gun. Also called “end-of-arm tooling” or simply the tool.

Workspace: The workspace or “work envelope” of a robot arm is the volume of 3D space that the end-effector can reach.

Major axes: The first three joints of the robot. The primary purpose of these axes is to determine the position of the end-effector.

Minor axes: The joints of the robot after the major axes. The primary purpose of the minor axes is to determine the orientation of the end-effector.

Coordinate frame: A set of three orthogonal axes obeying the right-hand rule.

Planar robot: A robot whose end-effector motion is limited to a single plane.

Spatial robot: A robot whose end-effector motion covers a volume of 3D space.

1.3 More About Robot Degrees-of-Freedom

To locate a rigid body in 3D space we must first attach a coordinate frame to it. To locate of the origin of this frame relative to a fixed reference frame requires three pieces of information. To orient this coordinate frame require another three pieces of information. So six pieces of information are required to specify the position and orientation of a rigid body in 3D space. It follows that a robot requires six DOF to be able to arbitrarily position and orient its end-effector. For this reason most robot arms have six DOF. Since each DOF adds to the robot's cost and complexity some robot arms are made with fewer DOF for specific applications (e.g. 3.5 DOF robots for electronic circuit board component insertion).

When a robot has more than six DOF for a given end-effector location there are many solutions for the joint positions. This type of robot is called a "redundant robot". These extra DOF give the robot additional flexibility but also make its control more complex.

Exercise 1.1: How many DOF does our arm have?

1.4 Common Spatial Robot Configurations and Workspaces

A robot's configuration is usually defined by the sequence of joint types making up its major axes. This also determines the shape of its workspace. A prismatic joint is denoted by P and a revolute joint by R. The following configurations of spatial robots are common:

Cartesian: Configuration of major axes is PPP. The workspace is a rectangular box. Please see the figures below. When this type of robot is hung from a rectangular frame it is called a "gantry robot" (named after a gantry crane).

Cylindrical: Configuration of major axes is RPP. The workspace is basically cylindrical in shape.

Spherical: Configuration of major axes is RRP. The workspace is basically spherical in shape.

Articulated: Configuration of major axes is RRR. This configuration is similar to the human arm and is the most common type of industrial robot. The workspace is basically spherical in shape.

SCARA: SCARA stands for Selective Compliance Assembly Robot Arm. SCARA robots have two revolute joints that are parallel and allow the end-effector to move in a horizontal plane plus a prismatic joint that provides vertical movement. Please see the figures below. Its joints are controlled such that they are more compliant (i.e. less stiff) in the horizontal plane than in the vertical direction. This helps the robot to compensate for position errors in the plane during component insertion. The workspace is basically cylindrical in shape.

Note 1: Normally an additional three revolute joints are used to orient the end-effector and form the set of minor axes. So, for example, the complete configuration for a Cartesian robot is denoted PPPRRR or 3P3R.

Note 2: The shape of the workspace also depends on the motion ranges of the joints.

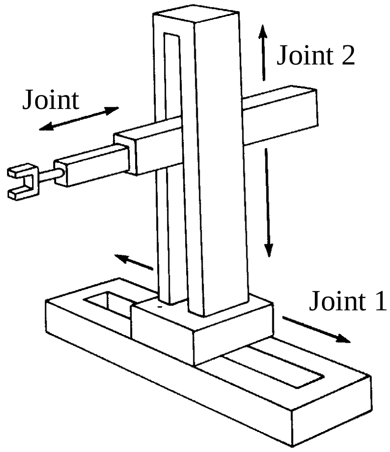


Figure 1.5 Major axes for a Cartesian robot [1].

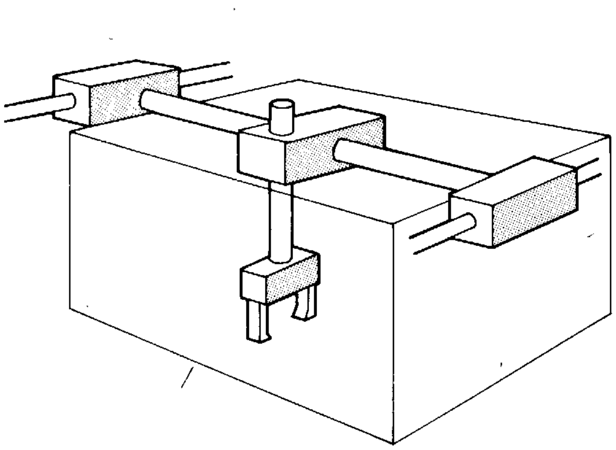


Figure 1.6 Workspace for a gantry robot [2].

Figure 1.7 A gantry robot for a welding application.

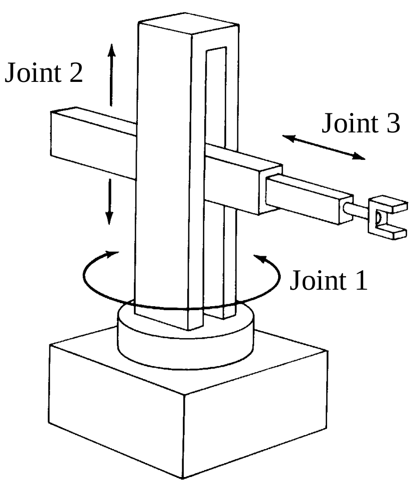


Figure 1.8 Major axes for a cylindrical robot [1].

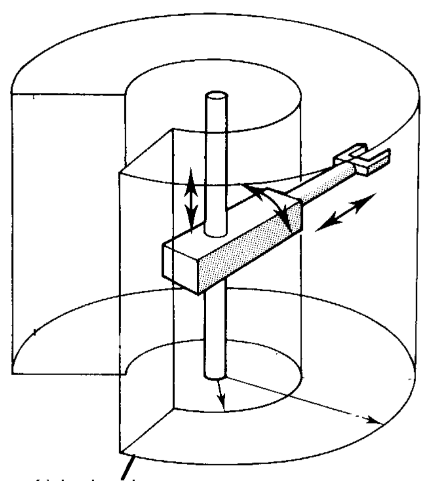


Figure 1.9 Workspace for a cylindrical robot [2].

Figure 1.10 A Seiko RT33 cylindrical robot.

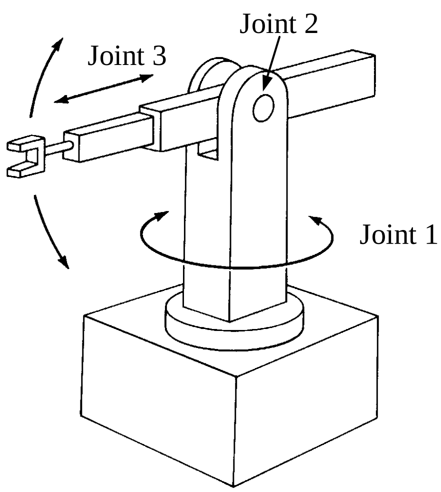


Figure 1.11 Major axes for a spherical robot [1].

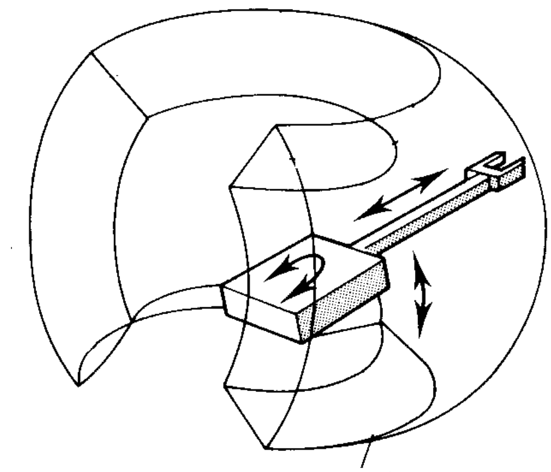


Figure 1.12 Workspace for a spherical robot [2].

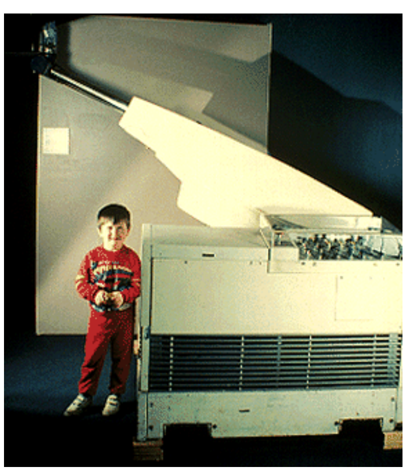


Figure 1.13 A Unimation "Unimate" spherical robot. This was the first industrial robot.

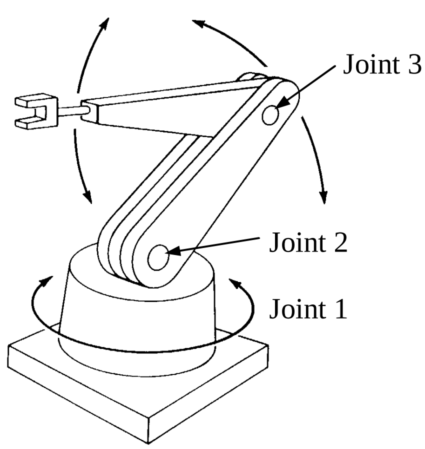


Figure 1.14 Major axes for an articulated robot [1].

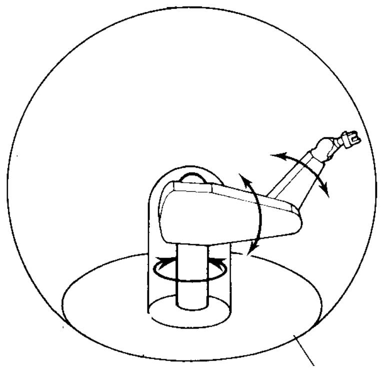


Figure 1.15 Workspace for an articulated robot [2].

Figure 1.16 A Motoman SV3X articulated robot.

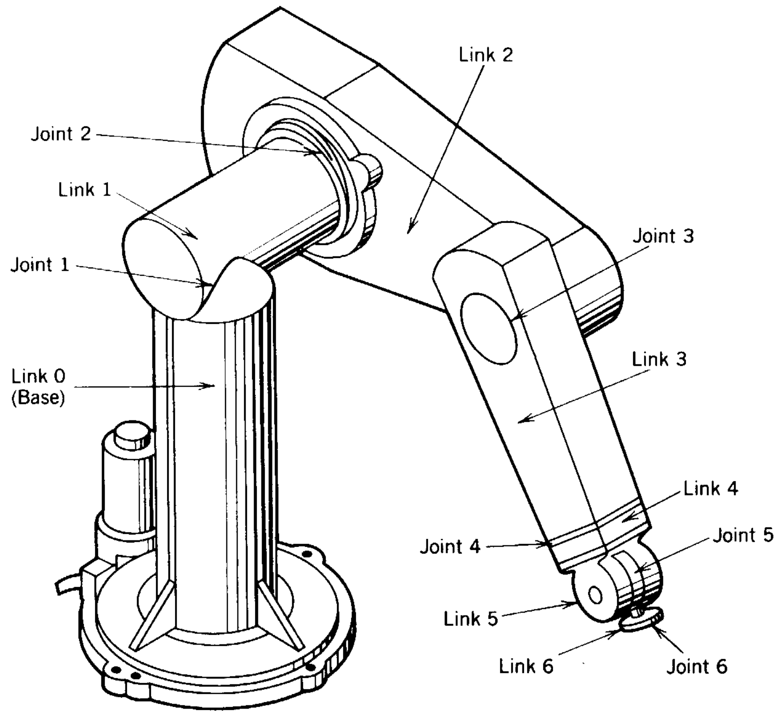


Figure 1.17 The links and joints of a Unimation PUMA articulated robot [1].

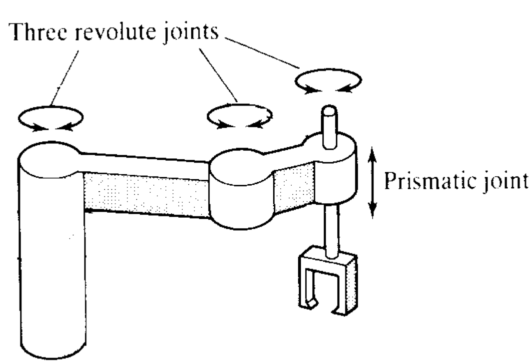


Figure 1.18 The joints of a SCARA robot [2].

Figure 1.19 An Adept Cobra 600 SCARA robot.

1.4.1 Graphical Method for Determining a Robot's Workspace

Steps:
1. Move the last joint over its full range of motion and draw the path of the end-effector. For a revolute joint this will be an arc, for a prismatic joint this will be a line segment.
2. Sweep the path from step 1 over the range of motion of the previous joint.
3. Repeat step 2 until all joints have been moved.
4. Properly dimension and crosshatch your drawing.

Exercise 1.2: Draw the workspace for a planar PR robot with the following properties: range of first joint = 0.5 m - 1.5 m, range of second joint = ±60º, and length of second link = 0.5 m.

Exercise 1.3: Draw the workspace for a SCARA robot with the following properties: range of first joint = ±60º, range of second joint = ±180º, range of prismatic joint = 0.2 m, length of first link=0.5 m and length of second link = 0.3 m.

1.5 Parallel Kinematic Robots

The manipulators discussed so far consist of a single series of links and joints connected to a fixed base. Robots with this kinematic structure (also called an "open-chain mechanism") are known as "serial manipulators". Recently some manipulators based on two of more series of link and joints connected in parallel have been introduced commercially (forming a "closed-chain mechanism"). These are known as "parallel kinematic robots" or simply "parallel robots". Examples are shown in the figures below. Although the course will focus on serial manipulators since they are much more common, some coverage will be given to parallel robots.

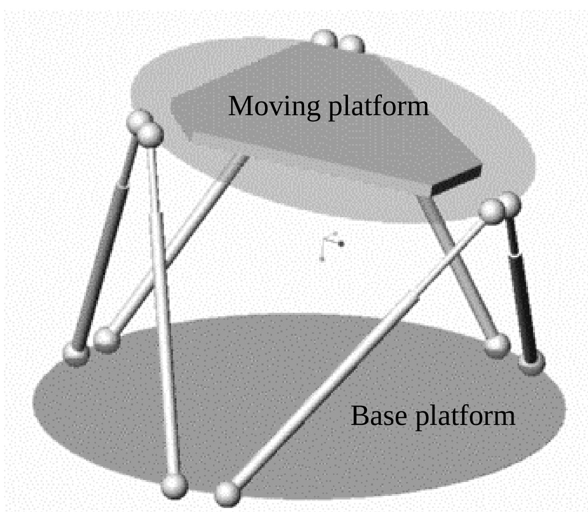


Figure 1.20 A six DOF parallel robot known as a "Stewart Platform". It features six active prismatic joints. These are connected to the base platform by universal joints (each with two passive DOF) and to the moving platform by spherical joints (each with three passive DOF). The end-effector is attached to the moving platform.

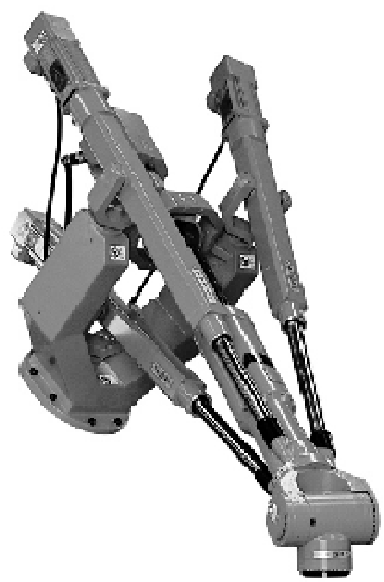


Figure 1.21 An ABB IRB 940 parallel robot. This robot uses three prismatic joints connected in parallel to form the major axes. Three serial revolute joints form the minor axes.

Figure 1.22 A Fanuc F200-i parallel robot. Its design is based on the Stewart plaform.

1.6 Robot Specifications

Payload: The mass a robot can carry and still remain within its other specifications. Normally a robot can carry a much larger mass than its specified payload but the deflections of the arm will cause the errors in the location of the end-effector to exceed the specified accuracy.

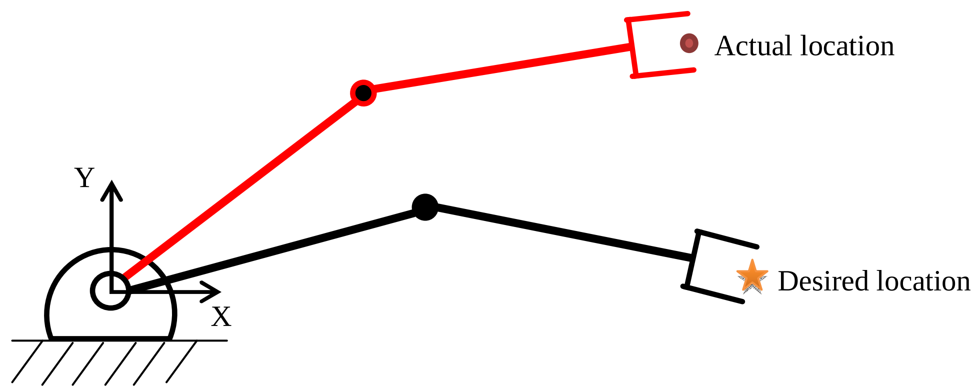
Accuracy: The maximum error between the desired location of the end-effector (normally commanded by the user program) and its actual location. This should be determined by a large number of tests at locations throughout the robot's workspace while carrying the specified payload. Note that this normally only applies to the endpoint of the motion path when the robot has stopped. Because the orientation error is typically very small, the accuracy is specified in terms of position only. The accuracy of most robots is much larger than their repeatability. Typically the accuracy is a few millimetres. Accuracy can be improved by calibration but can never be smaller than the repeatability.

Repeatability: A measure of the robot's ability to position the end-effector in the same place repeatedly. This captures the variability caused by such sources as backlash in the gears and flexibility in the links. Note that only the actual locations (and not the desired locations) need to be known to calculate the repeatability. As with accuracy a large number of tests should be used, and this spec. normally only applies to the endpoint of a motion path. Typically the repeatability is 0.1 mm or less. Also known as precision.

More details about Accuracy and Repeatability:

For a planar robot, the repeatability for one desired end-effector location equals the radius of the circle that encloses all of the measured actual locations (at least 100 of them). The robot should be commanded to approach this desired location from a variety of starting locations. The accuracy for this single location case is the radius of the circle centred at the desired location that encloses all of the actual locations. For a spatial robot and one desired end-effector location, the repeatability and accuracy are similarly defined by sphere radii. This process must be repeated for a grid of desired locations that fills the reachable workspace. The repeatability equals the maximum radius of the single-location repeatability spheres, while the accuracy equals the maximum radius of the single-desired-location accuracy spheres (or circles for a planar robot). An example of the single-desired-location accuracy and repeatability for a planar RR robot is shown in Figure 1.23.

For one test:



After 100 tests:

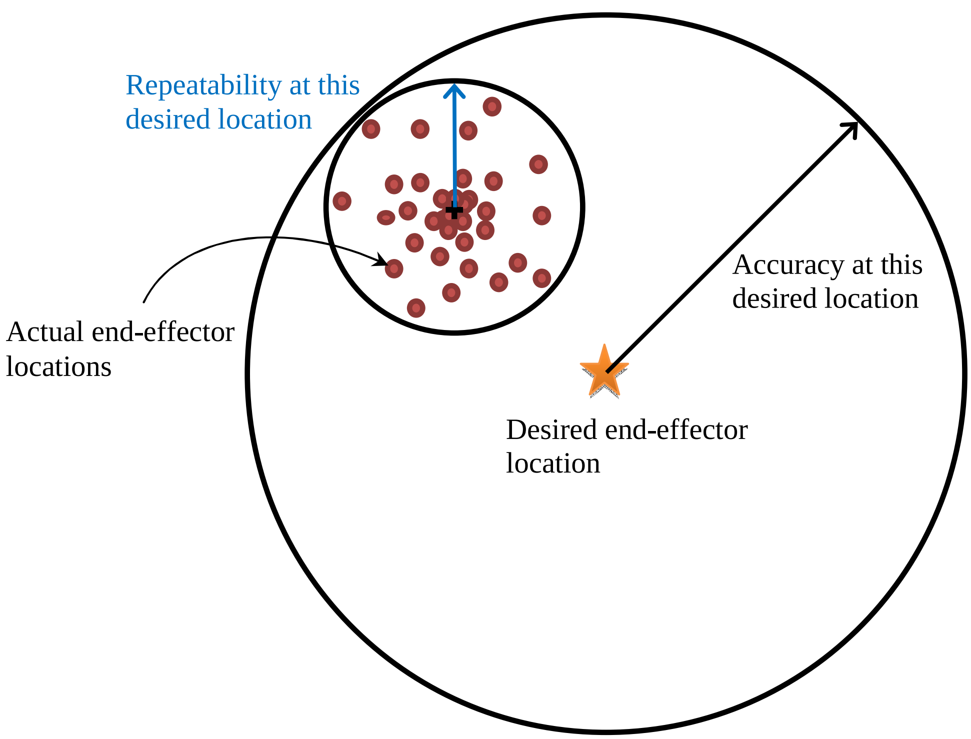


Figure 1.23 Example of the single-desired-location accuracy and repeatability for a planar RR robot. The errors have been exaggerated to make the drawing more clear. Please note that this figure by itself does not constitute the definition of repeatability or accuracy.

Maximum Speed: The maximum speed the end-effector can attain with the robot carrying the specified payload. Note that this is often not a meaningful spec. since we are usually more interested in the average speed. The average speed is a function of the end-effector's location, the acceleration and the distance moved.

Reachable Workspace: The volume of space the end-effector can reach in at least one orientation.

Dextrous Workspace: The volume of space the end-effector can reach with any desired orientation. This is a subset of the reachable workspace. Note: when the term *workspace* is used alone it refers to the reachable workspace.

Exercise 1.4: Which specs would be the most important for circuit board assembly?
Which specs would be most important for welding automotive frames?

1.7 Applications

The number of applications of robotics is growing steadily. Here are some examples:

Pick and place operations: The robot picks up parts and places them elsewhere. This includes loading and unloading parts from CNC machining centres or from forming presses (called "machine loading"), placing individual parts onto pallets (called "palletizing"), and other such tasks. The end-effector is some type of gripper.

Welding: Robots are used for many types of welding (spot, arc, laser, etc.). This is the most common use for robots in the automotive industry. Their consistent control of speed and position results in consistent weld quality.

Painting: Another common application in the automotive industry. Robots do the job well and save people from the toxic fumes.

Inspection: A robot alone cannot perform inspection but when its end-effector is a sensor such as a vision system it can be used be to scan and inspect parts for defects.

Assembly: Assembling component parts into a product is a particularly challenging application. This is because the tolerances between the parts to be mated may be tight so proper assembly may require careful pushing, turning, bending, etc. Still robotic assembly is often used particularly in electronics applications requiring a cleanroom environment (since robots are much cleaner than people).

Other manufacturing applications: Robots are also used for drilling, deburring, grinding, routing, waterjet cutting and glue dispensing.

Surveillance: The growing demand for security means that more mobile robots equipped with video cameras (and other sensors) and more vision systems (on their own or with robots) will be used. Vision systems are used for face recognition applications.

Policing, fire fighting, search and rescue: Another area where teleoperated mobile robots equipped with video cameras and manipulators are being increasingly used.

Hazardous environments: In the interest of human safety, robots are used in many hazardous environments, particularly in the nuclear industry.

Remote locations: These applications include space and underwater exploration, and pipeline repair.

Medicine: Robots are precise and do not suffer from fatigue – these capabilities make them well suited for surgery. These robots are teleoperated and allow surgery to be performed at a distance over a high speed network.

Assisting individuals: Universities and companies are developing assistive robots to help elderly and disabled people have greater independence.

Personal robots: These include robotic vacuum cleaners, lawnmovers, butlers, pets and toys.

Figure 1.24 A robot stacking boxes on a pallet (“palletizing”).

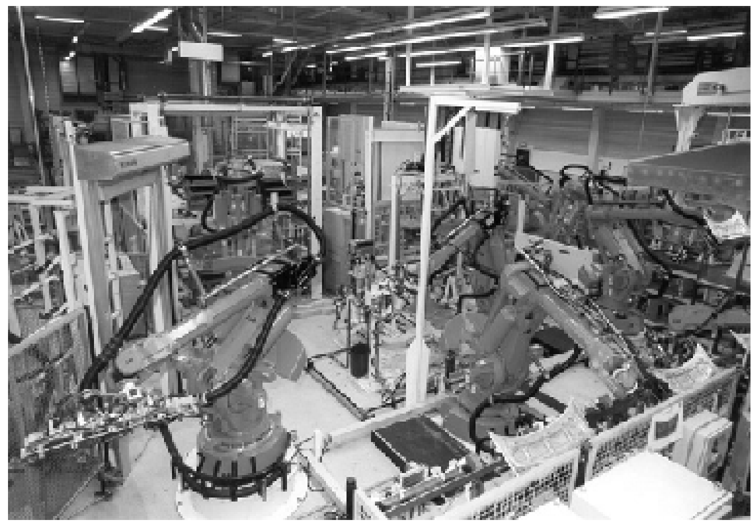


Figure 1.25 A workcell containing several robots for loading/unloading automotive parts.

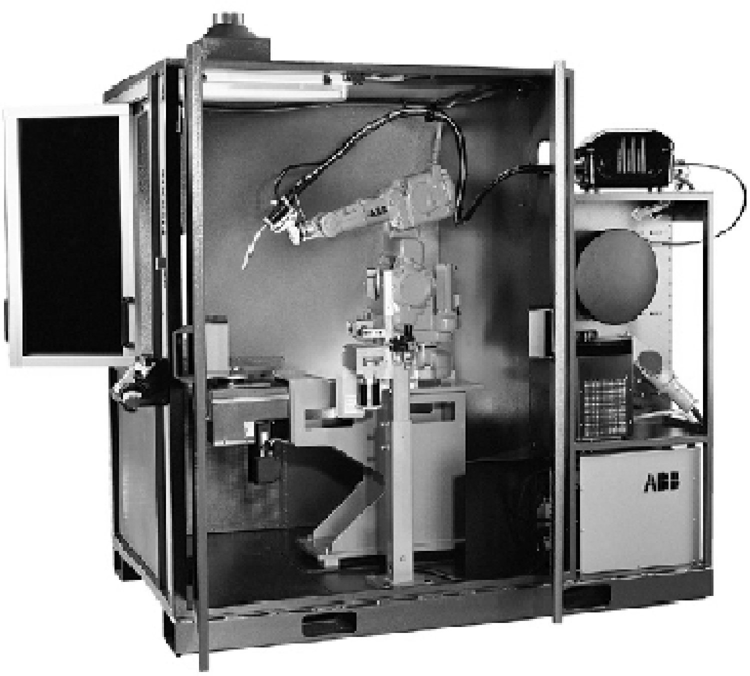


Figure 1.26 A robotic arc welding workcell.

Figure 1.27 The ESI MR-5 mobile robot for bomb disposal.

Figure 1.28 NASA has developed “Robonaut”, a robot designed for spacewalk repair missions. This robot is teleoperated and features two 14 DOF hands with human-like dexterity.

Figure 1.29 The Raptor Wheelchair Robot System made by Rehabilitation Technologies.

Figure 1.30 The PR2 robot from Willow Garage fetching a “cold one”.

1.8 Jobs in Robotics

People in the robotics field work on:
- robot design
- sensor design
- controls design
- computer programming
- workcell design
- system integration
- system maintenance
- robot programming

References

1. A.J. Koivo, “Fundamentals for Control of Robotic Manipulators”, John Wiley & Sons, 1989.
2. P. J. McKerrow, “Introduction to Robotics”, Addison-Wesley Publishing Company, 1991.