1-1 Reprogrammability, multifunctionality.

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1-2 Forward kinematics: Position and orientation of the end effector in terms of the joint variable

Inverse Kinematics: Joint variables in terms of position/orientation of the end effector.

Trajectory Planning: Planning the time history of the joint variables necessary for the robot to execute a given task.

Workspace: The total volume swept out by the end-effector as the manipulator executes all possible motions.

Accuracy: A measure of how close the manipulator can come to a given point within its workspace.

Repeatability: A measure of how close a manipulator can return to a previously taught point.

Resolution: The smallest increment of motion that can be sensed. The resolution is a function of the distance travelled and the number of bits of encoded accuracy.

Joint Variables: The relative displacement between adjacent links, denoted θ_i for revolute joins and d_i for prismatic joints.

Spherical Wrist: RRR wrist configuration with joint axes intersecting at a common point.

End Effector: A gripper or tool used to perform the robot's task.

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1-3 Geometry, power source, application area, method of control.

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1-4 Depending on the pattern to be followed, articulated, spherical, or cartesian manipulators may be used for applications such as welding, laying a bead of glue, cutting, grinding or sanding a surface, spray painting, auto assembly, and anthropomorphic tasks. Cartesian manipulators are also suited for table-top assembly and, as a gantry, for the transfer of material or cargo. SCARA manipulators are useful for table-top assembly and pick-and-place applications.

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1-5 **Non-servo robots:** Materials handling, servicing a special purpose machine such as a press.

Point-to-point robots: Materials handling, spot welding, forging.

Continuous path: Arc welding, grinding and deburring, spray painting, assembly, sheep shearing.

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1-6 Welding, painting, deburring, grinding, polishing.

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1-7 Automating inspection of goods for defects, monitoring unknown terrain, sorting objects by color or shape, painting an object, picking up randomly placed objects.

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1-8 Handling fragile objects (glass, eggs, etc.), grinding, assembly defusing explosives, machining.

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1-9 Latest figures and projections may be found in the current edition of *World Robotics*, published by the International Federation of Robotics, or a similar publication.

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1-10 The key point of this question is the rapidly of change. An overnight change would not allow time for workers to be retrained or to find other jobs, thus negating the beneficial effects of increased productivity. This point can be discussed at length in a classroom setting.

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1-11 Here again the key point is in the extreme nature of allowing no robotic automation. While no one would be put out of work by robots, the productivity and quality of goods produced would soon lag behind that of other countries. The long term effect would likely be higher unemployment than would result by phased automation. This point can also be discussed in a classroom setting.

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1-12 Applications involved reaching around or behind obstacles, assembly of a complex, intricate object, defusing explosives, artificial limbs.

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1-13 Using the law of cosines: $c^2 = a^2 + b^2 - 2ab\cos\theta$, let $a = \ell = b$ and $c = d$. Then $d^2 = 2\ell^2(1 - \cos\theta)$. Hence,

$$d = \ell\sqrt{2(1-\cos\theta)}.$$

With $\ell = 1$ meter , $\theta = 90°$, $d = \sqrt{2}$ meters $= 1.4142136$ meters. On the other hand, $s = \ell\theta = \frac{\pi}{2}$ meters $= 1.5707963$ meters. Resolution $= \frac{\text{Total distance}}{2^n}$ where $n =$ number of bits of encoder accuracy. The linear resolution is $\frac{\sqrt{2}}{2.2^{10}} = 0.003811 = 1.3811 \times 10^{-3}$ meters. The rotational resolution is $\frac{\pi}{2.2^{10}} = \frac{\pi}{2.2^{10}} = \frac{\pi}{2^{11}} = 0.001534 = 1.534 \times 10^{-3}$ meters.

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1-14 Resolution $= \frac{\ell\theta}{2^n} = \frac{(50cm)(\pi)}{2^8} = 0.6136\text{cm}.$

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1-15 $\ell = 0.5\text{meter} \quad \theta = \pi \qquad r = \frac{\text{total distance}}{2^n} = \frac{\frac{1}{2}\cdot\pi\cdot\frac{1}{5}}{2^8}m = 1.227 \times 10^{-2}cm.$

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1-16 The position of the TCP is not measured directly but is computed from encoder measuring joint positions. Thus, the accuracy is affected by computational errors, machining accuracy in construction of robot parts, etc.

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1-17 If direct end-pointing sensing were used, less uncertainty could enter the measurement of the end-effector position. Difficulties including introducing a vision system at the end-effector and feeding back the end-effector position which could cause the control system to become unstable.

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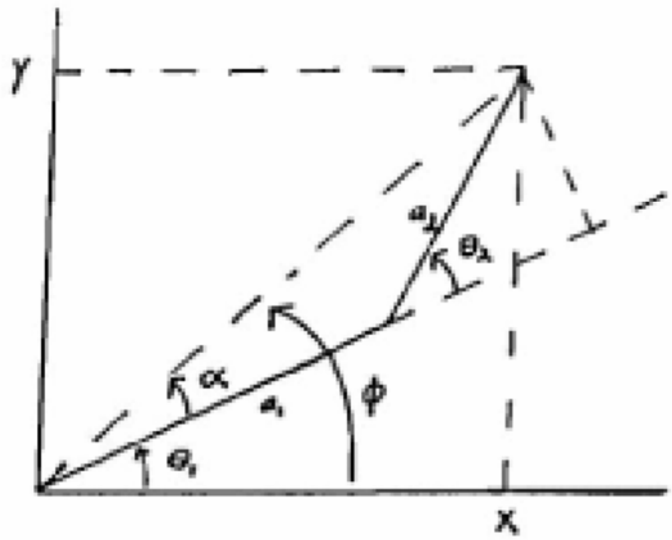

1-18 We have $\theta_1 = \phi - a$ where $\phi = \tan^{-1}(y/x)$; $a = \tan^{-1}\left(\frac{a_2 \sin\theta_2}{a_1 + a_2 \cos\theta_2}\right)$

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1-19 1.

$$
\begin{aligned}
x &= a_1\cos\theta_1 + a_2\cos(\theta_1+\theta_2) &= \cos\left(\frac{\pi}{6}\right)+\cos\left(\frac{2\pi}{3}\right) \quad 0.366025\\
y &= a_1\sin\theta_1 + a_2\sin(\theta_1+\theta_2) &= \sin\left(\frac{\pi}{6}\right)+\sin\left(\frac{2\pi}{3}\right) \quad 1.3660254
\end{aligned}
$$

2.

$$
\begin{aligned}
\dot{x} &= -\sin\theta_1 - 3\sin(\theta_1+\theta_2)\\
\dot{y} &= \cos\theta_1 + 3\cos(\theta_1+\theta_2)\\
\text{At}\ \ \theta_1 &= \theta_2 \ = \ \frac{\pi}{4},\\
\dot{x} &= -\left(\sin\frac{\pi}{4}+3\sin\frac{\pi}{2}\right) \quad = \quad -3.7071068,\\
\dot{y} &= \cos\frac{\pi}{4}+3\cos\frac{\pi}{2} \quad = \quad 0.7071068
\end{aligned}
$$

3. machine problem
4. machine problem

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1-20 If both links are equal length then $x = 0$, $y = 0$ can be reached by infinitely many configurations, namely $\theta_2 = 180°$, $\theta_1 =$ arbitrary.

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1-21 Moving a distal link with large mass will require more torque from all motors driving previous links. In addition, since momentum is the product of mass and velocity, a massive link far from the base may cause troublesome overshoot issues. We may reduce the mass of distal links in two ways:

1. driving distal joints from motors mounted on previous links, thereby eliminating the mass of the motor from the link mass. A consequence of this is the increased complexity of design due to trasmission of motion from motors to the joint they drive.

2. reducing the mass of the links themselves, either by selecting materials with less mass or by strategically boring holes in the link to reduce mass. The downside of this approach is seen in the control problem. For a robot whose links have small mass, picking up an object will drastically affect the dynamics of the manipulator. For more massive robots, manipulating small objects have less or negligible affect on the dynamics.

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