Work envelope

The **work envelope** refers to the **working volume** which can be reached by some point at the end of the Robot arm. It is sometimes also referred as the **work space**.

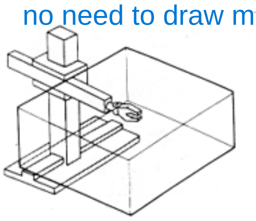
It is important for manufacturers to work with robotic companies or integrators to determine how much robotic workspace is needed when designing the system. If a facility is too small, it may not be suited for a large robot, or the robot's operation may be destructive. One thing that is necessary is that human workers stay out of a robot's workspace during operation. While humans may be able to enter each other's workspace, entering a robot's workspace could result in injury or death, due to the amount of speed and force with which a robot works.

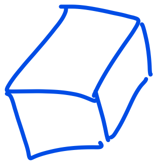
memorise one characteristics, advantages, applications will do

Cartesian robot

Cartesian robot has a cubic or rectangular work envelope

if asked to draw, a cubic will do, no need to draw machine





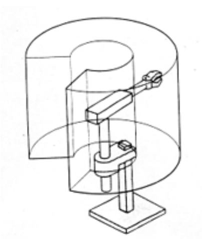
Characteristics
- Cartesian robot has three linear movements. There are no dead zones within the working envelope and the robot can manipulate its maximum payload throughout the working volume.

Advantages
- Cartesian robot has rigid structure and thus usually can offer good levels of precision and repeatability

Applications
- Cartesian robot is used for pick and place work, assembly operations, handling machine tools and arc welding

Cylindrical robot

Cylindrical robot has a cylindrical work envelope.



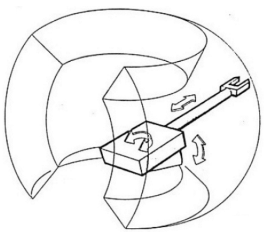
Characteristics
- Two linear movements, one rotational. The cylinder is hollow, since there is a limit to how far the arm can retract, this creates a cylindrical dead zone around the robot structure

Advantages
- Cylindrical robot is good for reaching deep into machines, save on floor space, and tend to have the rigid structure needed for large payloads.

Applications
- Cylinder robots are used in assembly operations, handling of machine tools, spot welding, and handling at die cast machines.

Spherical robots / Polar robot

Spherical robots has a spherical work envelope



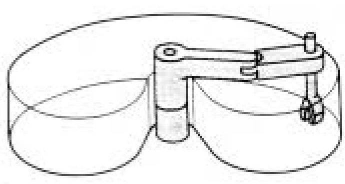
Characteristics
- A spherical robot has 1 linear axis, 2 rotating axes
- Long horizontal reach but with short vertical reach

Advantages
- Rigid structure and easily visualize
- Large workspace for size
- Easily computed kinematics.

Applications
- Palletizing, loading and unloading
- Material transfer, foundry and forging

Selective Compliance Assembly Robot Arm (SCARA)

SCARA robot has kidney shaped prism of work envelope, having a circular hole passing through the middle.



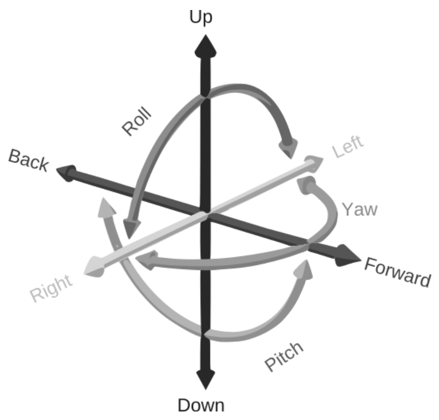
Characteristics
- A SCARA robot has 1 linear axis, 2 rotating axes

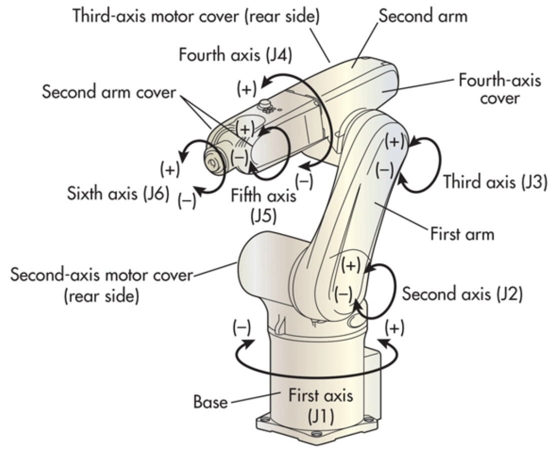
Advantages
- Excellent repeatability and fast cycle times
- Large workspace
- Height axis is rigid

Applications
- Pick-and-place or assembly operations where high speed and high accuracy is required.

Robot Manipulator Workspaces: https://www.youtube.com/watch?v=hIRZeYgcG5E

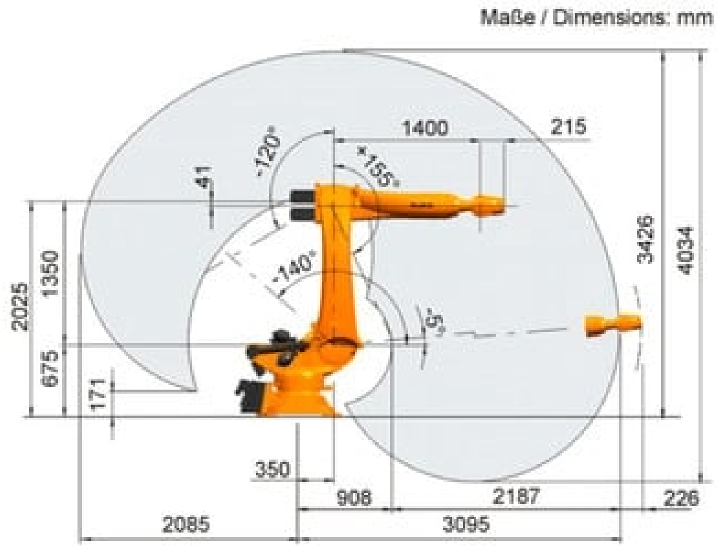
For a robot manipulator to be able to arbitrarily position and orientate an object in 3D space, the manipulator should have 6 degrees of freedom, i.e., 3 for positioning a point on the object and 3 for orienting the object with respect to a reference coordinate frame. Specifically, the body is free to change position as forward/backward (surge), up/down (heave), left/right (sway) translation in three perpendicular axes, combined with changes in orientation through rotation about three perpendicular axes, often termed yaw (normal axis), pitch (transverse axis), and roll (longitudinal axis).





Articulated robot

(a)



(b)

https://www.youtube.com/watch?v=7coUcEHxnYA&ab_channel=RobotWorx

https://www.youtube.com/watch?v=DJ7RofnnOm4&t=145s&ab_channel=ChanAdam

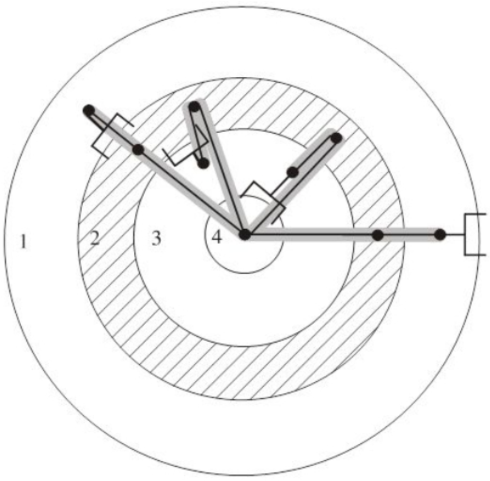
*Very Important, > 10 Marks

Generally, a robot's workspace can be classified into **reachable workspace** and **dexterous workspace**.

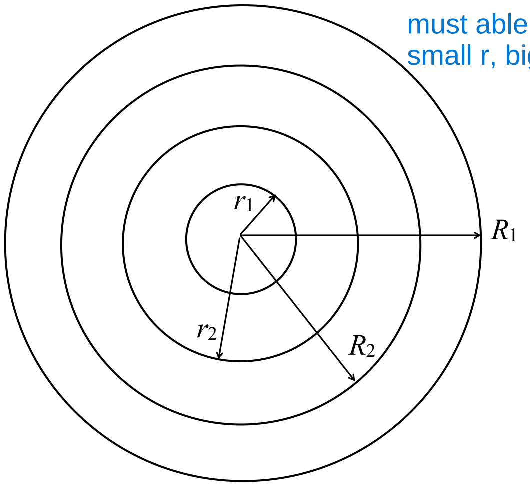
at least one orientation use these formulas

The reachable workspace is the volume whereby the end-effector is capable of reaching **each point** within the space in at **least one orientation**. For the **reachable workspace**, the outer radius is $R_1 = \lambda_1 + \lambda_2 + \lambda_3$ and the inner radius is $r_1 = \max\{\ |\lambda_1 - \lambda_2| - \lambda_3,\ |\lambda_2 - \lambda_3| - \lambda_1,\ |\lambda_1 - \lambda_3| - \lambda_2,\ 0\ \}$.

The **dexterous workspace** has the end-effector capable of reaching **all points in all orientations**. For the dexterous workspaces, outer radius is $R_2 = \lambda_1 + \lambda_2 - \lambda_3$ and the inner radius is $r_2 = \lambda_1 - \lambda_2 + \lambda_3$.



must able to draw this small r, big R



formulas not given, must be able to calculate and explain

For example,

For the **reachable workspace**, the end-effector of that workspace can reach:

Link length (m)	$\|\lambda_1 - \lambda_2\| - \lambda_3$	$\|\lambda_2 - \lambda_3\| - \lambda_1$	$\|\lambda_1 - \lambda_3\| - \lambda_2$	r_1	R_1
$\lambda_1 = 3,\ \lambda_2 = 1,\ \lambda_3 = 1$	$\|3-1\|-1=1$	$\|1-1\|-3=-3$			
$\lambda_1 = 3,\ \lambda_2 = 1,\ \lambda_3 = 2$					
$\lambda_1 = 3,\ \lambda_2 = 2,\ \lambda_3 = 1$					

For the **dexterous workspace**, the end-effector of that workspace can reach:

Link length (m)	$r_2 = \lambda_1 - \lambda_2 + \lambda_3$	$R_2 = \lambda_1 + \lambda_2 - \lambda_3$
$\lambda_1 = 3,\ \lambda_2 = 1,\ \lambda_3 = 1$		
$\lambda_1 = 3,\ \lambda_2 = 1,\ \lambda_3 = 2$		
$\lambda_1 = 3,\ \lambda_2 = 2,\ \lambda_3 = 1$		

$\cos(a+b) = \cos a \cos b - \sin a \sin b$

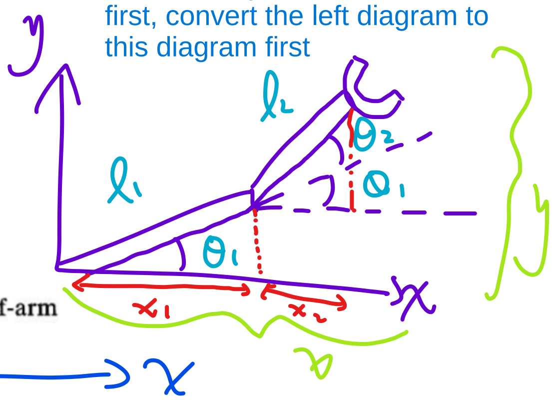
$\sin(a+b) = \sin a \cos b + \sin b \cos a$

make sure can explain these two

Forward Kinematics (FK):
Given the joint angles of a robotic arm, forward kinematics calculates the position and orientation of the end effector. It follows a straightforward computation using transformation matrices.

Inverse Kinematics (IK):
Given the desired position and orientation of the end effector, inverse kinematics determines the required joint angles. This is more complex as multiple or no solutions may exist, often requiring numerical methods or optimization techniques.

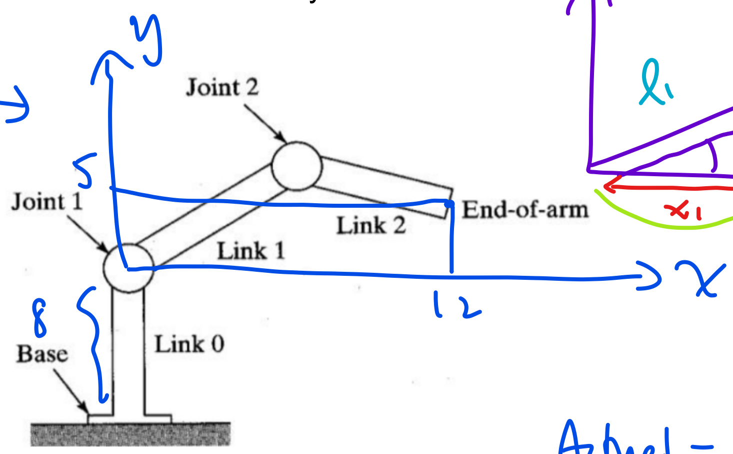
first, convert the left diagram to this diagram first



Determine the forward kinematics and the velocity for this robot:

Focus on this part only

can ignore this part



Actual = (12, 5+8)

*Refer to Discord Week 9 Notes

a) Forward kinetics is important for planning the motions for robotic manipulators. It enables the determination of where the end-effector will be located in the workspace for a given set of joint angles.

b) Find the forward kinematic of the manipulator

$$x = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2)$$
$$= l_1 \cos\theta_1 + l_2 \cos\theta_1 \cos\theta_2 - l_2 \sin\theta_1 \sin\theta_2$$

$$y = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2)$$
$$= l_1 \sin\theta_1 + l_2 \sin\theta_1 \cos\theta_2 + l_2 \sin\theta_2 \cos\theta_1$$

c) Find the velocity of the manipulator

$$\frac{d}{dx}\sin(x) = \cos(x)$$
$$\frac{d}{dx}\cos(x) = -\sin(x)$$

Velocity $= \frac{dx}{dt}$ (rate of change of x) $= \dot{x}$

$= \frac{dy}{dt}$ (rate of change of y) $= \dot{y}$

$$x = l_1 \cos\theta_1 + l_2 \cos\theta_1 \cos\theta_2 - l_2 \sin\theta_1 \sin\theta_2$$

$$\frac{\partial x}{\partial \theta_1} = -l_1 \sin\theta_1 - l_2 \sin\theta_1 \cos\theta_2 - l_2 \cos\theta_1 \sin\theta_2$$
$$= -l_1 \sin\theta_1 - l_2(\sin\theta_1 \cos\theta_2 + \cos\theta_1 \sin\theta_2)$$
$$= -l_1 \sin\theta_1 - l_2 \sin(\theta_1 + \theta_2)$$

$$\frac{\partial x}{\partial \theta_2} = -l_2 \cos\theta_1 \sin\theta_2 - l_2 \sin\theta_1 \cos\theta_2$$
$$= -l_2(\cos\theta_1 \sin\theta_2 + \sin\theta_1 \cos\theta_2)$$
$$= -l_2 \sin(\theta_1 + \theta_2)$$

$$y = l_1 \sin\theta_1 + l_2 \sin\theta_1 \cos\theta_2 + l_2 \sin\theta_2 \cos\theta_1$$

$$\dot{x} = \frac{\partial x}{\cancel{\partial \theta_1}} \times \frac{\cancel{d\theta_1}}{dt} + \frac{\partial x}{\partial \theta_2} + \frac{d\theta_2}{dt}$$
$$= [-l_1 \sin\theta_1 - l_2 \sin(\theta_1 + \theta_2)]\dot{\theta}_1 - l_2 \sin(\theta_1 + \theta_2)\dot{\theta}_2$$

same method for y

$$\dot{y} = \frac{\partial y}{\partial \theta_1} \times \frac{d\theta_1}{dt} + \frac{\partial y}{\partial \theta_2} \times \frac{d\theta_2}{dt}$$

Path integration

- Path integration uses basic geometry to work out the position of a robot, given an initial position and knowledge of the movement that occurred.
- A simple case is where the robot makes independent rotations and straight line movements. It could use an optical encoder on its wheels to estimate the heading angle θ and the distance travelled, d. Then $x_t = x_{t-1} + d\cos\theta$ and $y_t = y_{t-1} + d\sin\theta$. Problems with path integration occur because small errors in the distance or heading estimate can accumulate into large errors in position.
- A popular solution is to have some external reference points in the world that can be used to recalibrate the system. These points are called landmarks. They are perceptual distinctive features in the environment that the robot can recognise, preferably from difference viewpoints, and use to orient itself.
- A road sign is an example of an artificial landmark (i.e. one introduced for the purpose of navigation) whereas a tree might serve as a natural landmark, i.e. something already existing in the environment that can be adopted for navigation. Good properties for a landmark is that it does not move or change, can be detected over a wide area, and is unique.

The points below are enough for us to score full marks

Explain how robot can navigate safely while avoiding obstacles

Sensors like cameras, LiDAR, ultrasonic sensors, and GPS collect environmental data to detect obstacles, determine position, and generate a real-time map using Simultaneous Localization and Mapping (SLAM). The onboard processor analyzes this data to make navigation decisions and sends commands to actuators, such as motors, that control the wheels and robotic arms. Effectors, including wheels and grippers, carry out the physical actions needed for movement and book delivery. By functioning together, these components allow the robot to navigate efficiently, avoid obstacles, and complete deliveries successfully.

will ask to compare different type of actuators for given scenario

Actuators

Electric actuators convert electrical energy into mechanical motion using motors such as servo, stepper, or linear actuators. They provide high precision, fast response, and energy efficiency, making them well-suited for automation and precise movement. Compared to hydraulic actuators, which generate high force using pressurized fluid, electric actuators are cleaner, require less maintenance, and are more efficient but may not deliver the same force output. Pneumatic actuators, powered by compressed air, enable rapid motion but are less precise and energy-efficient due to air compressibility. While hydraulic and pneumatic actuators are ideal for high-force applications, electric actuators excel in robotics where accuracy and efficiency are crucial.

E.g.: Question mention 1 sensor is not sufficient, what is the proposed solution for this issue?
Ans: Integrate multiple sensor, which is known as sensor fusion.....

Sensor fusion

Sensor fusion enhances robot behavior and decision-making by integrating data from multiple sensors, improving perception and accuracy. Individual sensors have limitations, such as noise, blind spots, or environmental interference, but combining data from different sources provides a more reliable and comprehensive understanding of the surroundings.

In autonomous robots, for example, merging data from LiDAR, cameras, ultrasonic sensors, and GPS enables precise navigation and object detection, even in challenging environments. Sensor fusion helps robots distinguish obstacles from safe pathways, enhances localization accuracy, and supports better decision-making by leveraging multiple data points.

Additionally, it improves redundancy and fault tolerance, allowing robots to continue operating even if one sensor fails. By processing and analyzing data collectively, sensor fusion increases efficiency, adaptability, and intelligence, making robots more effective in applications such as self-driving cars, industrial automation, and medical robotics.

Physical Interference of Robots

- Here the work volumes of the robots in the cell are overlapping, posing dangers of collision. Collisions can be prevented by separating the robots so that their work volumes are not overlapping.
- However, there are cases where the robots work on the same component piece or where the robots in turns, work on the component. Here the programmed work cycles of the robots must be coordinated so that they will not be near enough to risk a collision.

start from here not so important, the rest very important

Machine Interference

Machine interference occurs when two or more machines are being serviced by one robot. It can be measured as the **total idle time** of all the machines in the cell as compared to the **robot cycle time**. The measure is commonly expressed as a percent as follows,

$$\text{Machine interference} = \frac{\text{Total idle time of machine, } T_i}{\text{Total cycle time of robot, } T_c} \times 100\%$$

Total cycle time for each machine, T_c = processing time, T_m + robot/worker servicing time, T_s
(machine run time) (robot/worker loading and unloading)

$$\text{Maximum number of machines in the cell} = \frac{\text{Total cycle time for each machine, } T_c}{\text{robot/worker servicing time, } T_s + \text{repositioning time , } T_r}$$

Example 1:
A four-machine cell in which a robot is used to load and unload the machines. Each of the four machines is identical with identical cycle times of 72 s. This cycle time is divided between run time (52 s) and service time (load/unload) by the robot (20 s). If each machine has an idle time of 8 seconds during its cycle while the robot is fully occupied throughout its work cycle, calculate the machine interference of the work cell.

- In the example, when the robot cycle time is greater than the machine cycle time, there will be resulting machine interference. If the machine cycle time is greater than the robot cycle time, there will no machine interference, but the robot will be idle for part of the cycle. In cases where the service and run times of the machines are different, the above relationships become complicated by the problem of determining the best sequence of servicing times for the machines into the robot cycle time.

Example 2:
In a machine cluster which produces industrial products, an industrial robot will service n production machines. Each production machine is identical and has an automatic processing time T_m = 40 seconds. The robot servicing time for each machine is given by the equation T_s= 10 + 3n, where T_s is the servicing time in seconds. T_s increases with n because more time is needed to move the robot arm as n increases. The full cycle time for each machine in the cell is $T_c = T_m + T_s$.

a) Determine the maximum number of machines in the cell such that there is no machine interference.
b) Compute the machine cycle time T_c.
c) Compute the robot work time.
d) Compute the robot idle time.
e) Determine the hourly production rate of this machine cluster.

Example 3:
In a machine cluster, the appropriate number of production machines to assign to the worker is to be determined. Let n = the number of machines. Each production machine is identical and has an automatic processing time T_m = 4 minutes. The servicing time T_s= 12s for each machine. The full cycle time for each machine in the cell is $T_c = T_m + T_s$. The repositioning time for the worker is given by T_r = 5 + 3n, where T_r in seconds. T_r increases with n because the distance between machines increases with more machines.

a) Determine the maximum number of machines in the cell if no machine idle time is allowed.
b) Compute the machine cycle time T_c.
c) Compute the worker idle time expressed as a percent of the cycle time.