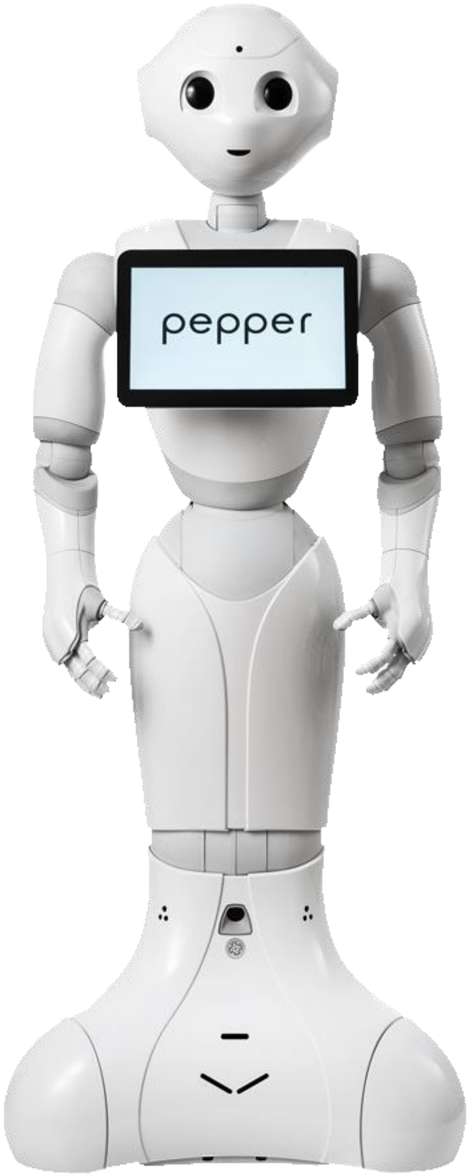
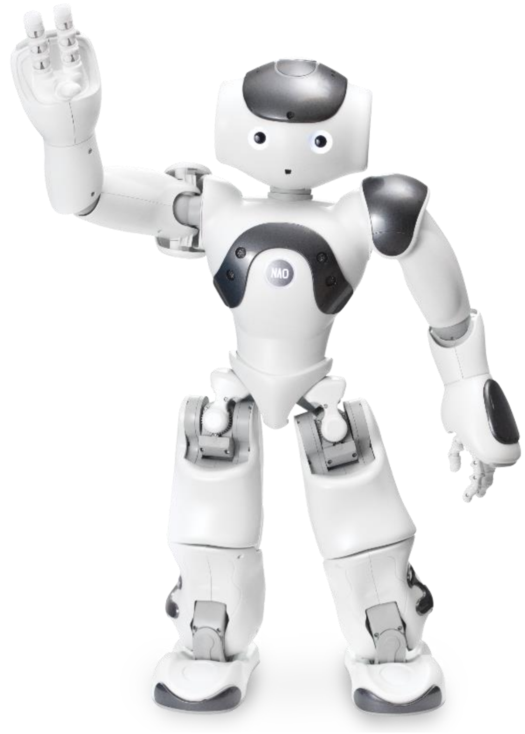
Fundamentals of Robotics

Robot Manipulators 01

We have different kinds of robots at Sukkur IBA CRAIB Lab





Kinematics basic

C-Workspace

Workspace

Task space

Types of Joints

Grubler's Formula

Degree of Freedom

End Effector and its types

Kinematic diagrams

Coordinate Frames

Denavit-Hartenberg rules

Standard 3 DoF Manipulators

Spherical Wrist of Manipulators

Robots

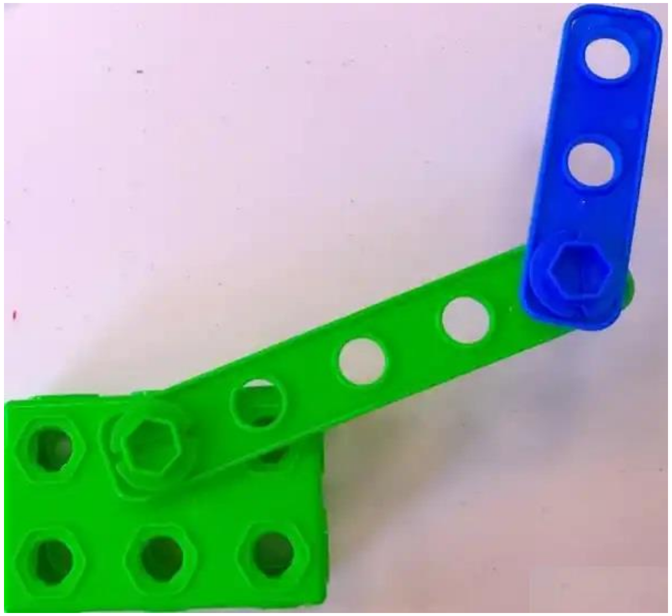
- A robot consists of **links** and **joints**.
- Every joint connects exactly two links.
- **Actuators**, which can be, for instance, electric motors, will provide **forces** and **torques** and cause the links to **move**.
- Ideally, the actuators are of **lower speed** and **high torque**, but available actuators have speeds in the **range of thousands of RPMs**, and **speed reduction** and **torque amplification** using gears.

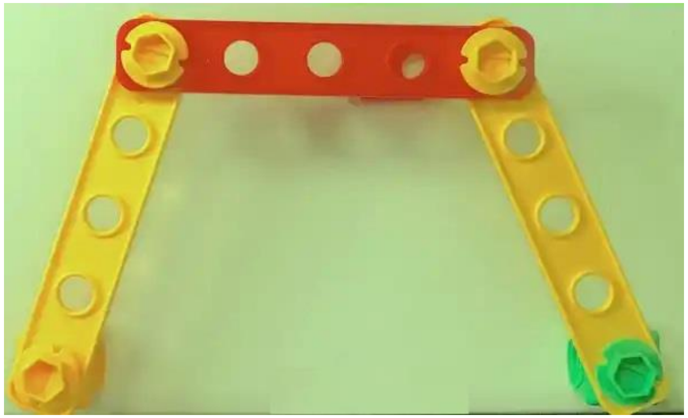
Robots Sensors

- Different **sensors** can also be equipped on the robot.
- For instance, to measure the **position of the joints**, **encoders** are installed on the joints.
- **Tachometers** can be used to **measure velocity**, and **force/torque** sensors are needed when a robot is exerting force on the environment, such as the task of writing on the board with chalk.
- **Vision** sensors such as **cameras** are also ubiquitous to **localize** objects in the environment of the robots.

Robots

- Robots can be **open-chain serial or closed-chain** with **closed loops**.
- When we stand with both our feet on the ground, we form a closed-chain, and our arm, when is allowed to move freely in space, is an example of an open-chain mechanism.
- The figure shows the four-bar-linkage, which is a closed chain mechanism.



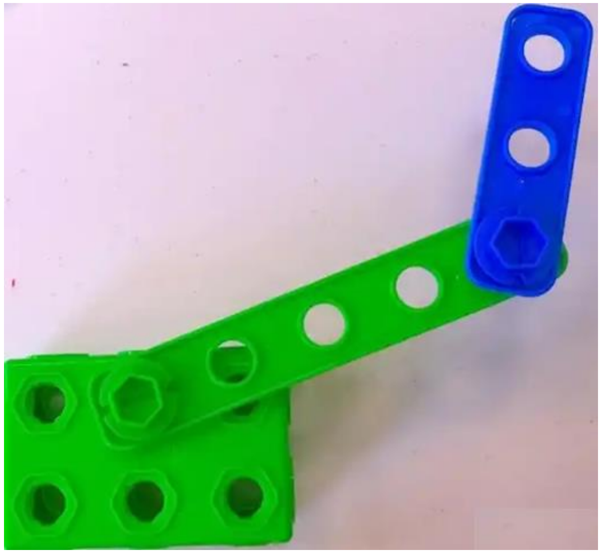


Configuration Space of a Robot

- The **configuration** of a robot is a specification of the position of all points of the robot.
- A space of all configurations of the robot is called the configuration space or C-space of the robot.
- The configuration of the robot is a point in its C-space

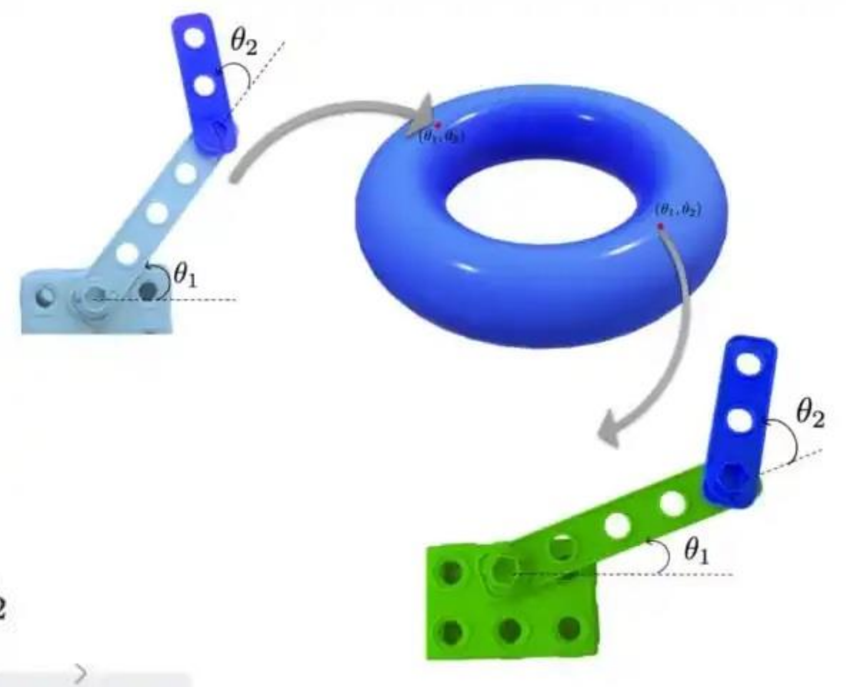
Configuration Space of a Robot

- Consider a **two-degrees-of-freedom planar** toy robot in the figure.
- It has two degrees of freedom because the **two joints** provide **two rotational** degrees of freedom.
- Suppose that the two angles can freely change between **0 and 360** degrees. The first link can trace a circle.
- For every angle of the joint one, the second link can trace a **circle** too.
- we can see that the c-space of a 2 link robot arm has a **torus or donut** shape. In fact, the **c-space** is the 2-dimensional surface of a donut:



Configuration Space of a Robot

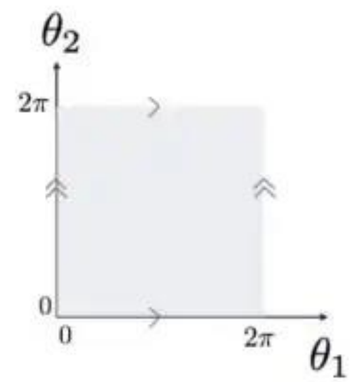
- For every configuration of the robot, there is a **unique point on the torus** and for every point on the torus, there is a unique configuration of the robot.
- So, the configuration of this robot can be represented by its two joint angles:



2R robot arm

Torus

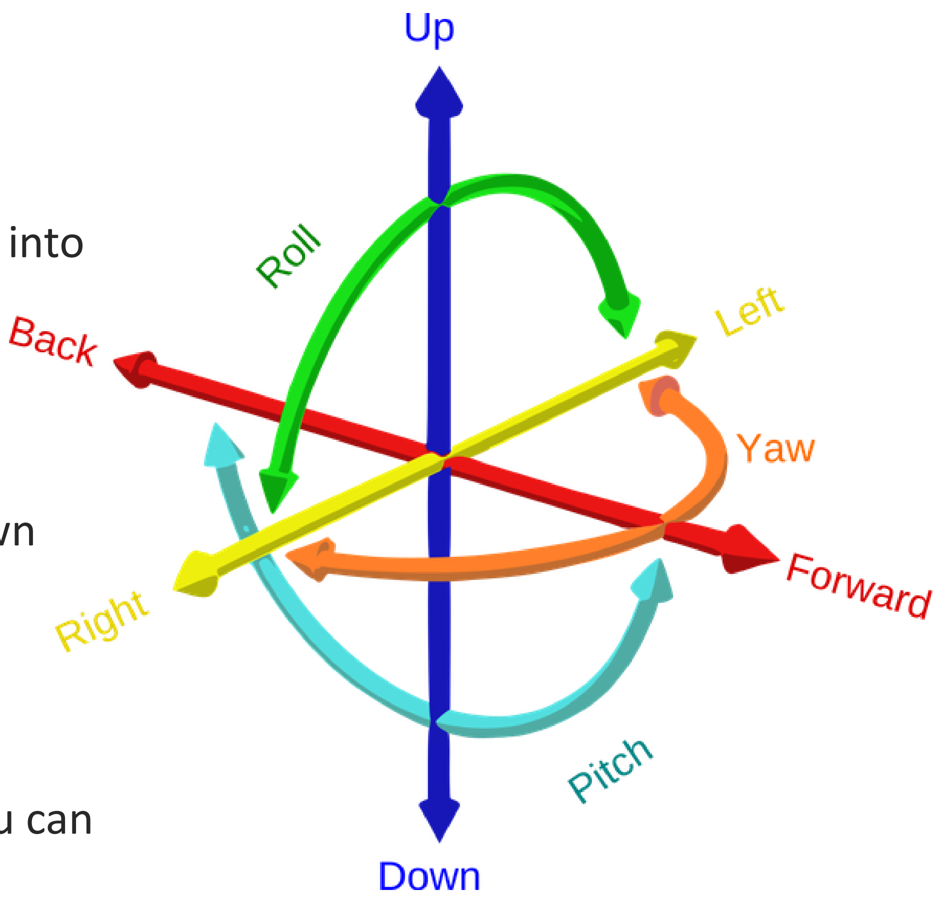
$$T^2 = S^1 \times S^1$$



$[0, 2\pi) \times [0, 2\pi)$

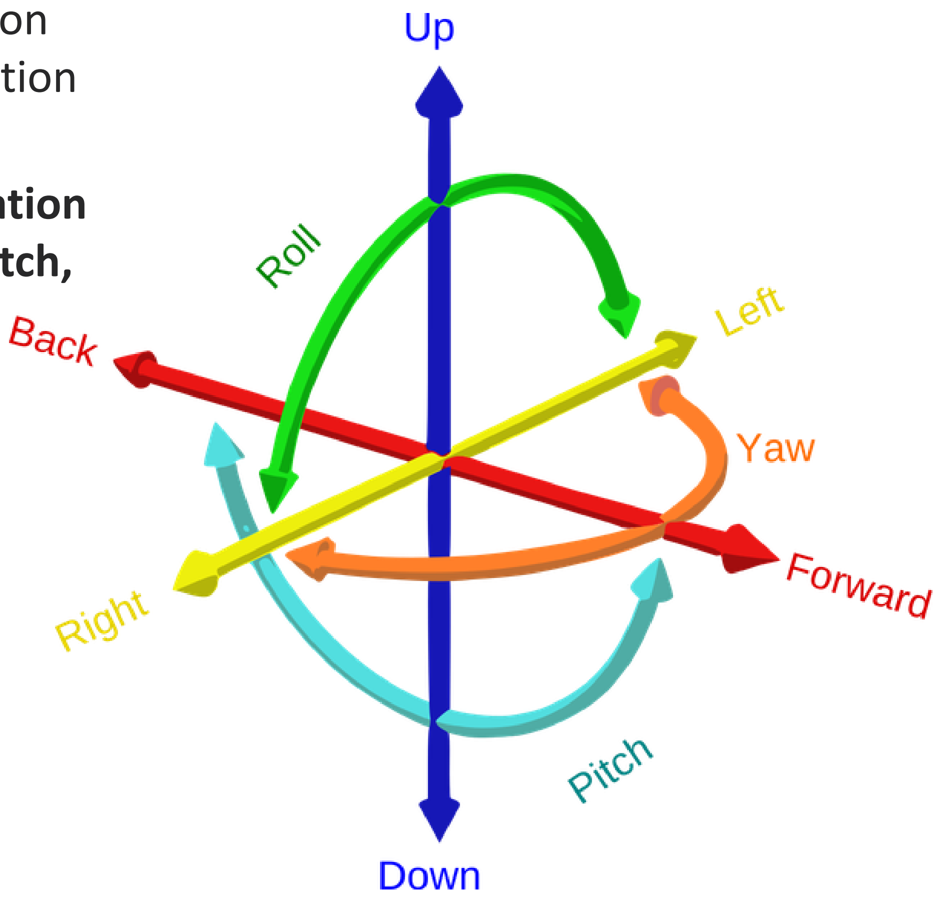
Degree of Freedom

- **Degree of freedom** basically refers to the number of ways in which an object can **move**. Now, simply put, there are **2** fundamental means of movement:
  - **Translation**
  - **Rotation**
- **Translation** can be further broken down into **3 kinds** of movements:
  - **Forward - Backward**
  - **Left - Right**
  - **Up-Down**
- **Rotation** can also be further broken down into **3 kinds** of movements:
  - **Pitch**
  - **Yaw**
  - **Roll**
- These are the **6 degrees of freedom.** You can get a better understanding from this diagram.



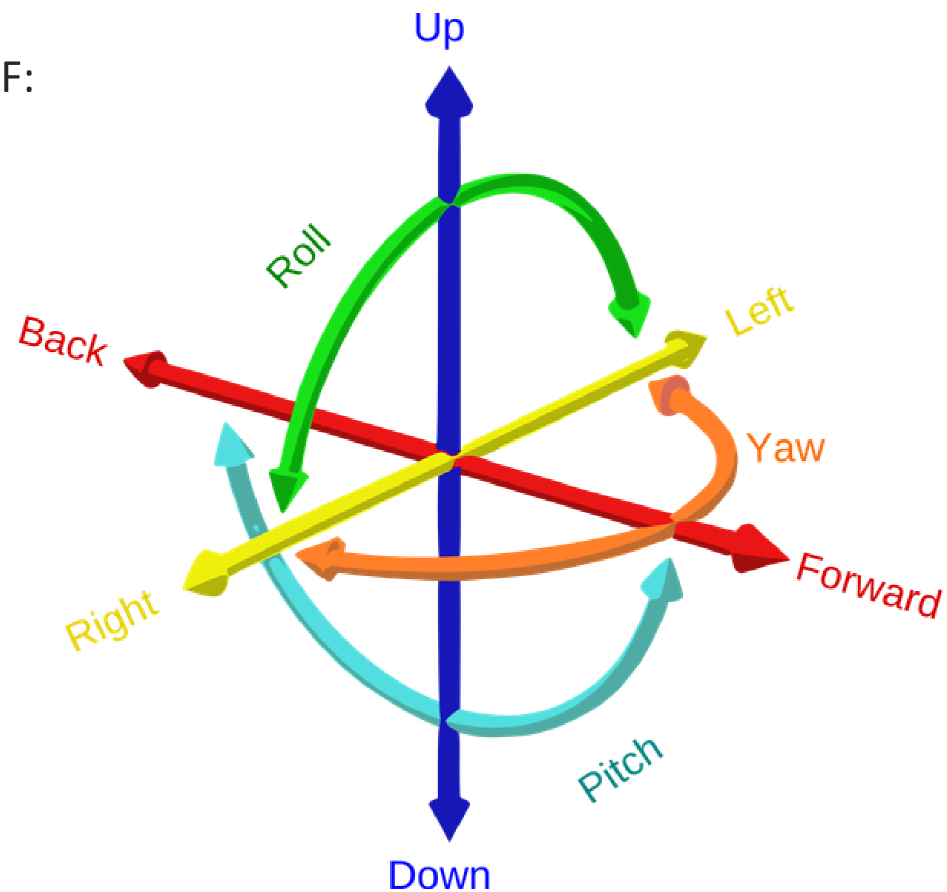
Degrees of Freedom of a Rigid Body in a 3D Space

- A **rigid body** in **three-dimensional space** has **six** degrees of freedom (DOFs).
- Three of them are for the position: motion along the **x**, motion along the **y**, and motion along the **z**.
- The other three are for **orientation**: **rotation around x** or **roll, rotation around y** or **pitch, and rotation around z** or yaw:



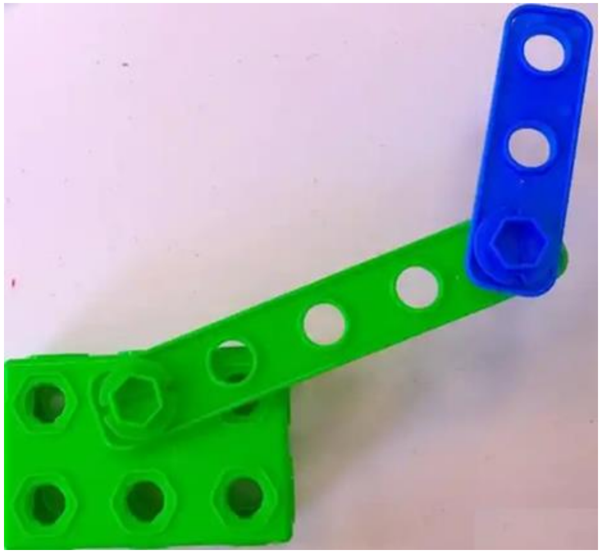
Degrees of Freedom of a Rigid Body in a 2D Space

- With the same analogy, we can say that the rigid body on a **2D plane** has **three degrees of freedom.**
- **Two linear** DOFs and **one rotational** DOF:



Robot Joints Put Constraints on the Motion of the Robot Links Reducing Their Degrees of Freedom (DOFs)

- We have seen that a rigid body in a **2D space** has **Three DOFs**, but why does a **two-DOF planar robot** with **two rigid** bodies have only **two DOfs**?
- The answer to this question lies in the **constraints** that its joints put on the **links**' movement with respect to each other.
- This robot has two **revolute** joints. Each of the joints put **two constraints** on the movement of the links. That is, its links can **only rotate around the z-axis**.



Degrees of Freedom (DOFs) of a 3R Robot Arm

- If we imagine a robot in **3D** like a **3R robot** (with **three revolute joints**) in space with three revolute joints.
- The revolute joint (**R**) will put **five constraints** on the motion of one link with respect to the other link. So again, it will provide only one DOF.
- So, we can conclude that **constraints** on the robot links **come from joints**.
- But how many **different joints** are used in robots?

Types of Different Joints Used in Robots

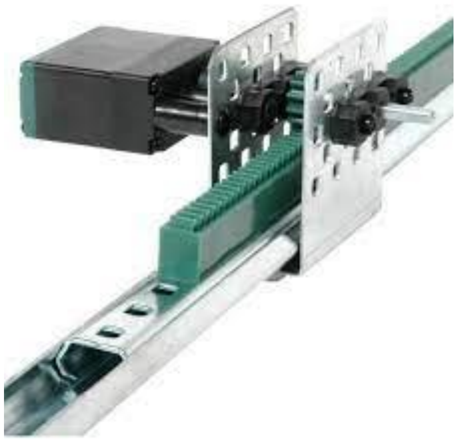
- The main types of robot joints are:
  - Revolute (Rotary) Joints
  - Prismatic or Linear (sliding) Joints
  - Universal Joints (U)
  - Spherical Joints (S)
  - Cylindrical Joints (C)
  - Helical Joints (H)

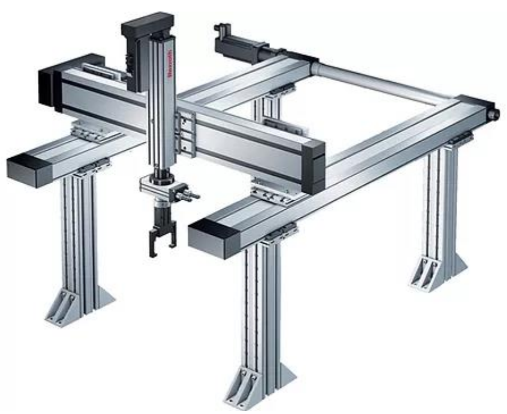
Revolute (Rotary) Joints

- Provide **One** degree-of-freedom (DOF) for the Robot Links.
- As we see in the **industrial robot** of the figure, a **revolute joint** is like a door hinge. It provides **one DOF** of motion between two bodies that it connects.
- The rotation is **around the joint axis**, and the **positive rotation** can be determined using the RHR (Right Hand Rule):
  - According to the RHR, if your **thumb** is in the direction of the joint axis, the positive rotation is the direction your other **4 fingers curl.**

Linear (sliding) or Prismatic Joints

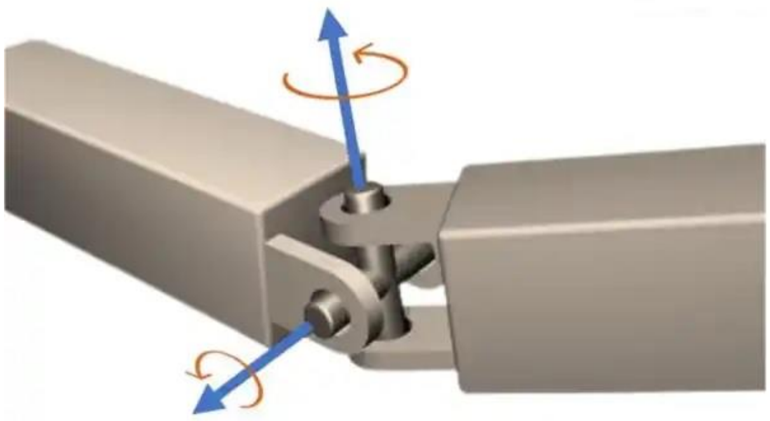
- Provide **One** degree-of-freedom (DOF) for the Robot Links.
- A **linear**, **sliding** or **prismatic** joint (P) provides a **linear motion** between two links.
- Prismatic joints provide single-axis sliding.
- Often prismatic joints are driven by rotary motors with a transmission that **converts rotational motion to linear motion**, such as a **ball screw** or a **rack and pinion**





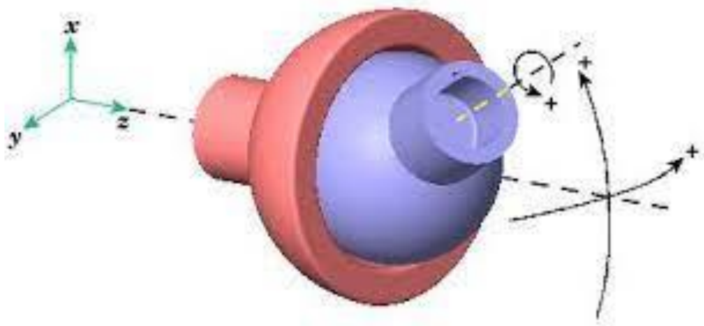
Universal Joints (U)

- Provide **two** Degrees of Freedom for the links they connect.
- The universal (**U**) joint, which is **two revolute joints** with joint axes **orthogonal** to each other.
- It can provide **two rotational** DOFs around **roll** and **pitch** axes that are **x and y axes**.



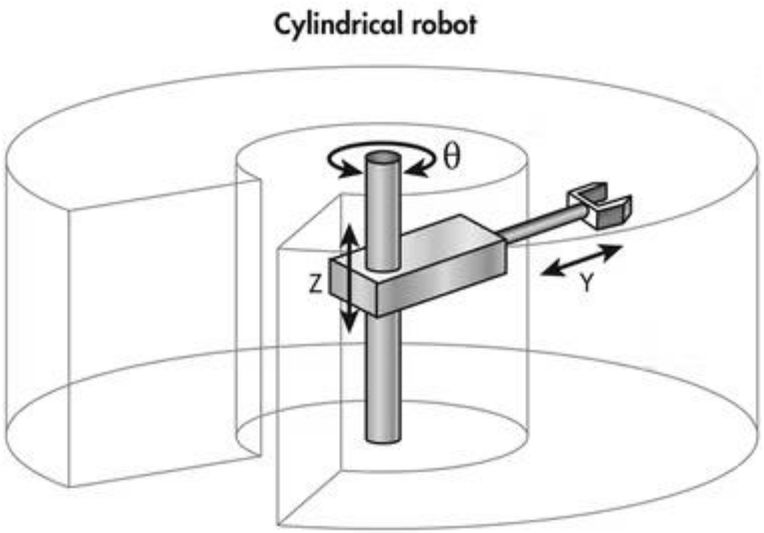
Spherical Joints (S)

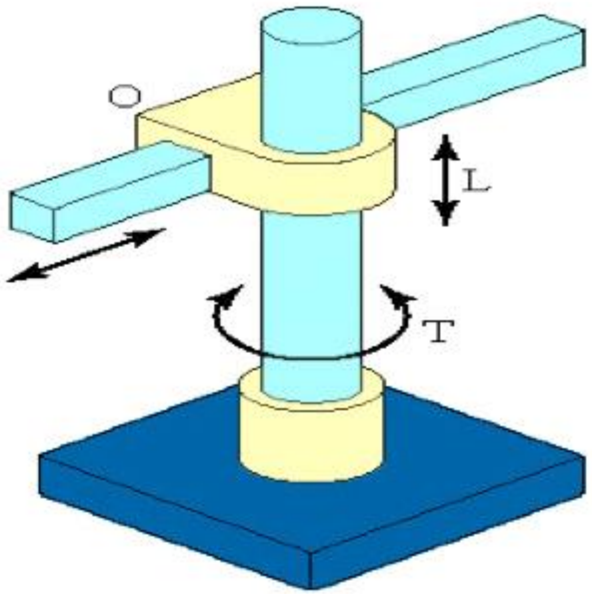
- Provide **three** Degrees of Freedom between the connecting links.
- The spherical (**S**), **ball-and-socket**, or **shoulder joint**, which are **two degrees of freedom of the U joint** plus **spinning** about the joint axis:



Cylindrical Joints (C)

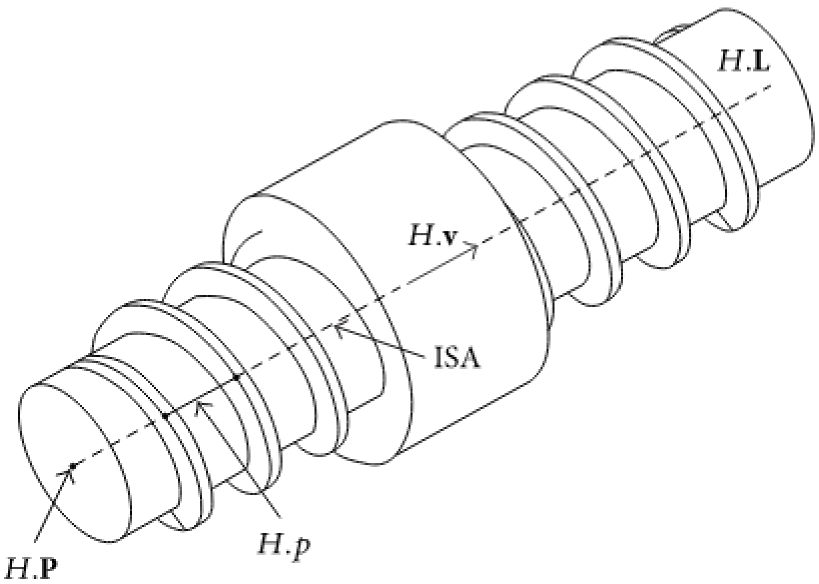
- Provide **two Degrees of Freedom** between the connecting links
- Cylindrical (**C**) joint that can provide an **independent translation** and **rotation** about a **single fixed joint axis**; thus, it has two DOFs.





Helical Joints (H)

- Provide **One Degree of Freedom** (DOF) Between the Rigid Bodies they Connect
- The helical (**H**), or **screw joint** that provides a **simultaneous rotation and translation** about a **screw axis** and can provide **one** degree of freedom
- The **difference between this joint and the cylindrical joint** is that in the cylindrical joint, the **rotation and translation** are **independent,** thus providing us with two degrees of freedom (DOFs).
- In the helical joint, linear motion is simultaneous, so it only has one degree of freedom



Grübler's Formula

- **Grübler's Formula** to **find** the degrees of freedom of any mechanism including the robots
- Grübler's Formula is a general formula that can be used to find the degrees of freedom of any mechanism and not just the robots.

$$\text{dof} = m(N - 1 - J) + \sum_{i=1}^{J} f_i$$

- N = # of bodies or links including ground
- J = # of Joints
- if m is the number of degrees of freedom of a single body, that is six for spatial bodies and three for planar bodies:
- m = 6, for spatial bodies
- m = 3, for planar bodies

Grübler's Formula on 2 DoF Planar Robot

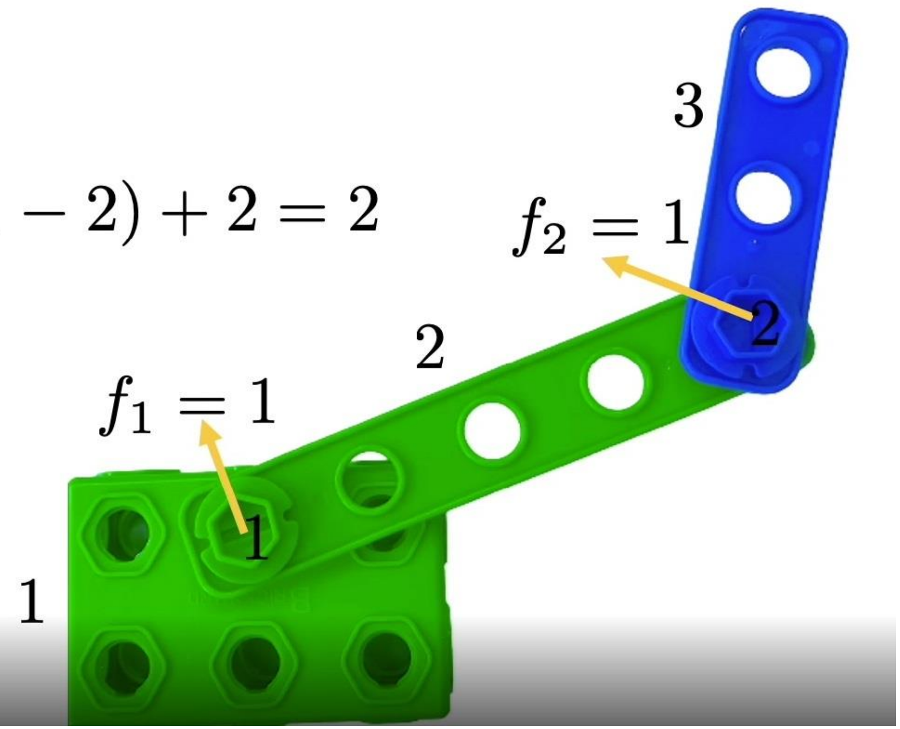
$$m = 3$$

$$N = 3$$

$$J = 2$$

$$\sum_{i=1}^{2} f_i = 2$$

$$dof = 3(3 - 1 - 2) + 2 = 2$$



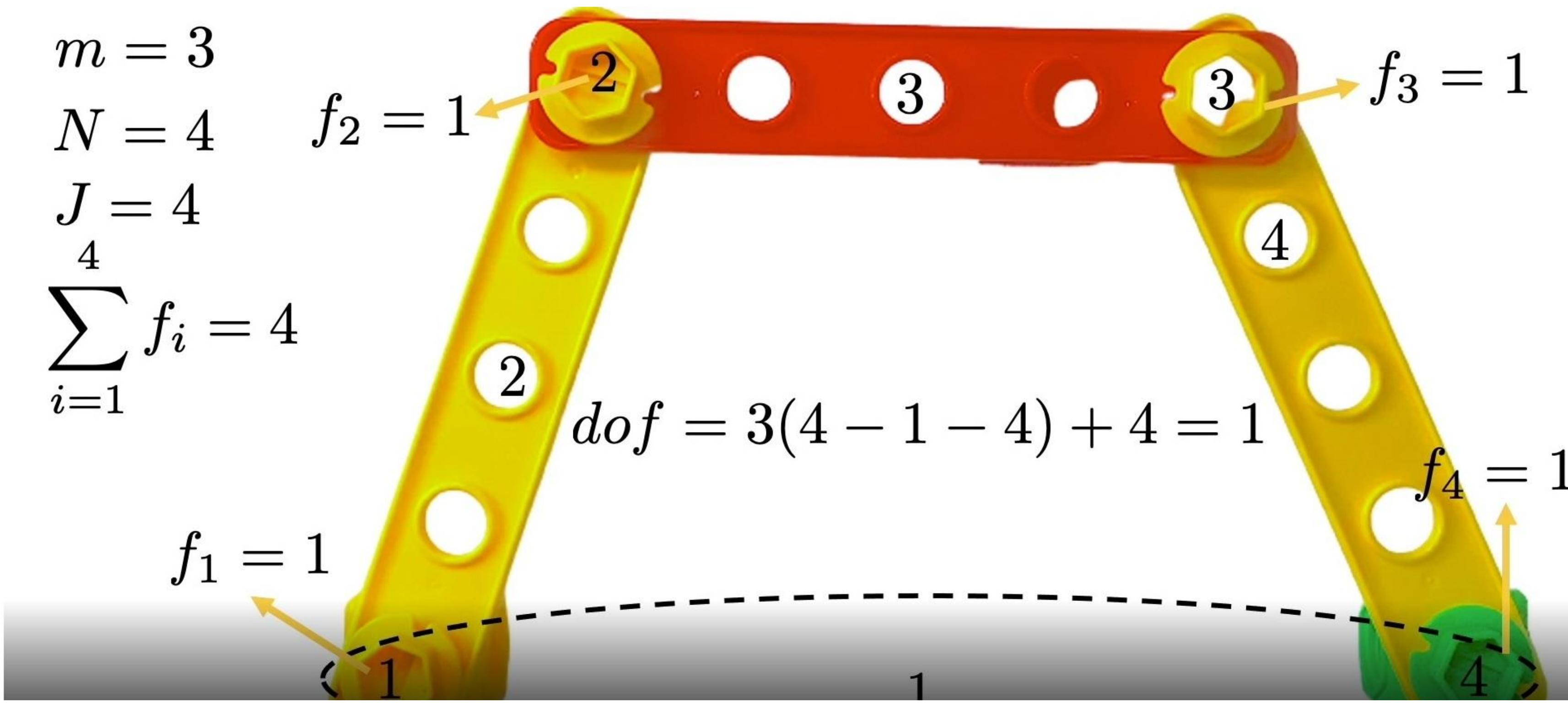
Grübler's Formula on 4-Bar Linkage

$$m = 3$$

$$N = 4$$

$$J = 4$$

$$\sum_{i=1}^{4} f_i = 4$$



$$dof = 3(4 - 1 - 4) + 4 = 1$$

Grübler's Formula on Stewart Platform

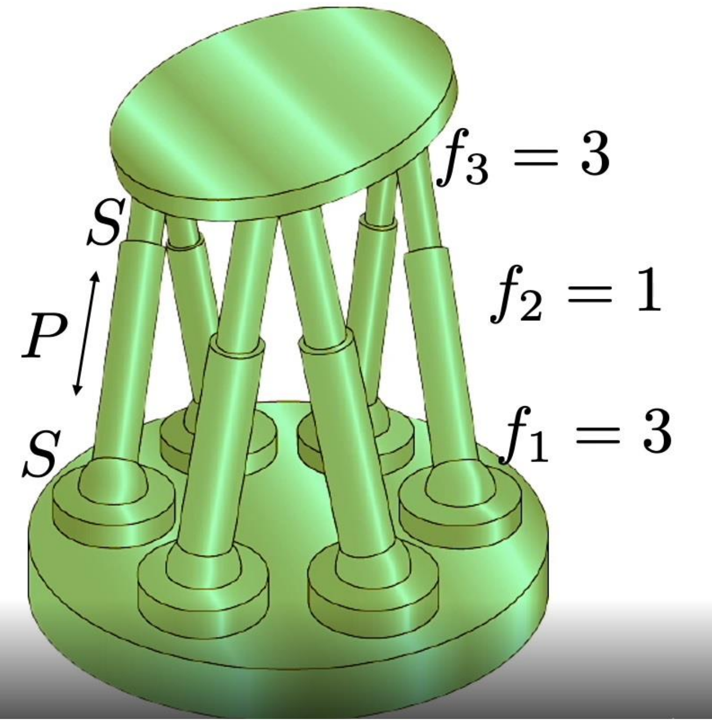
$$m = 6$$

$$N = 1 + 1 + 6(2) = 14$$

$$J = 6 \times 3 = 18$$

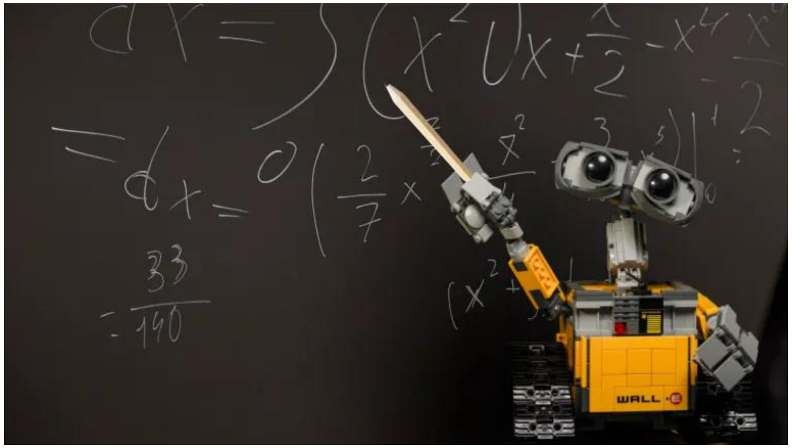
$$\sum_{i=1}^{18} f_i = 12 \times 3 + 6 \times 1 = 42$$

$$dof = 6(14 - 1 - 18) + 42 = 12$$



Task Space and Workspace for Robots

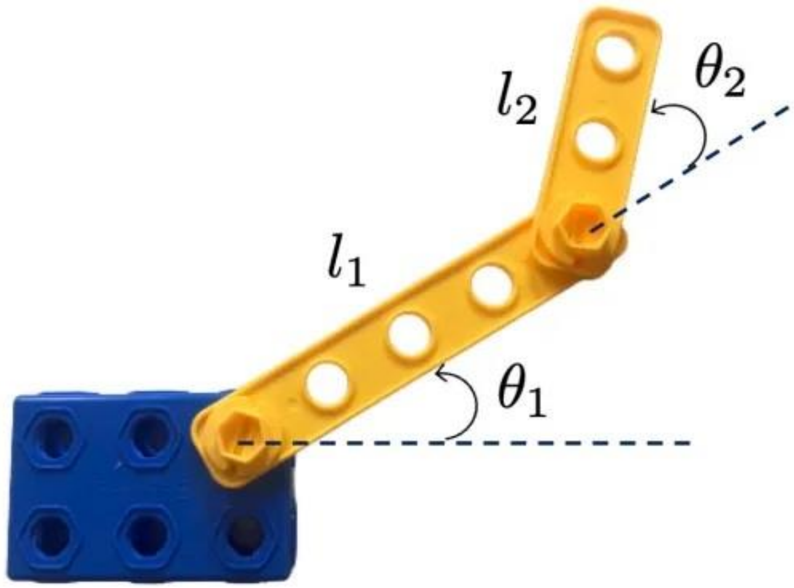
- By definition, the **robot's task** space is the space in which the robot's task is naturally expressed.
- We should **only know about the task and not the robot** to find the task space, and it is possible that the robot cannot reach some configurations.
- Example: If the task is to control the position of the tip of a marker on the board, then the task space is the Euclidean plane:
- The decision of **how to define the task space** is driven by the task **independently** of the robot. For instance, a pick and place task may require only 3 DOFs while the robot arm has 6 DOFs.



The Workspace of a Robot

- By definition, the **workspace** of a robot is **a specification of the reachable configurations** of the **end-effector**.
- The workspace of a robot has nothing to do with a particular task.

- Example: Suppose a planar robot arm below where the lengths of **two links** are **not equal**:

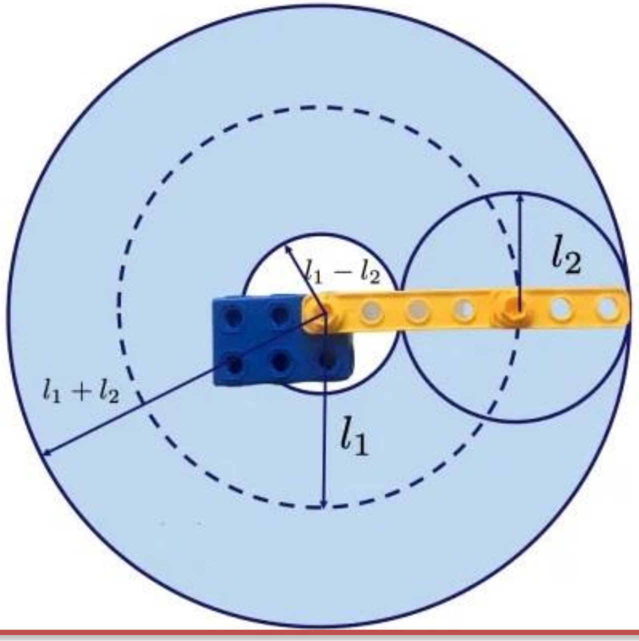


The Workspace of a Robot

- The robot arm has **two revolute joints**, and the lengths of the links are as follows:

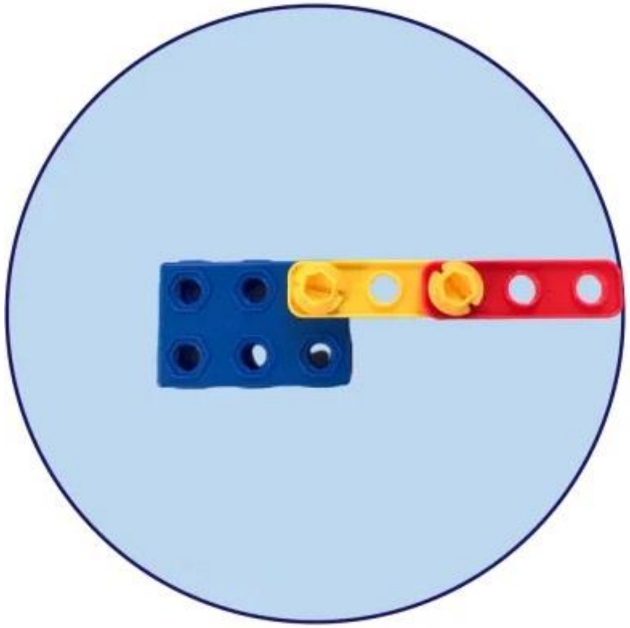
$$l_1 = 15.6\ cm$$
$$l_2 = 9.2\ cm$$

- The workspace of this robot, if we do **not impose** any **limitations** on the joint angles (both angles can be **freely changed** from **0 to 360º**), can be visualized like the figure below:
- The **circle** with a **radius** of ***$l_1 - l_2$*** is the **area** that the robot end-effector **cannot reach**.



The Workspace of a Robot

- If the lengths of the two **links** are **equal**, that is $l_1 = l_2$ then the robot's workspace can be visualized as follows:
- Note: The **workspace** is the **reachable configurations** of the **end-effector** of the robot.



Robot Manipulator

- **Robotic arms** can be used **to automate the process** of placing goods or products onto pallets.
- By automating the process, **palletizing** becomes more **accurate**, **cost-effective**, and **predictable**.
- The use of robotic arms also **frees human workers** from performing tasks that present a **risk** of **bodily injury**.
- We call the robot arm a **manipulator**, as the robot arm doesn't always **look like a human arm**.

Robot Arm = Manipulator
Joints + Links = Manipulator

- **Joints** are the parts of the manipulator that **allows movement**. Joints are **powered** and **controlled** using **motors**.
- **Links** are those parts that **connect joints** together.

Robot Manipulator (End effector)

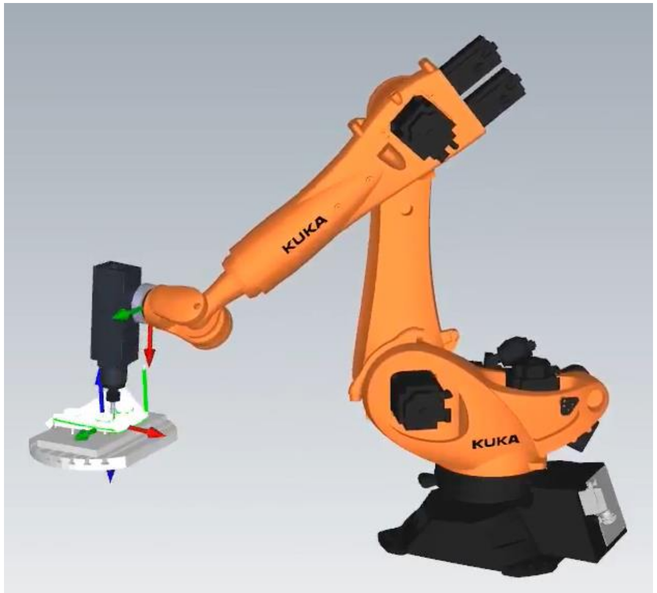
- An **end effector** is a **peripheral** device that attaches to a **robot's wrist**, allowing the robot to **interact with its task**.
- Most end effectors are **mechanical or electromechanical** and serve as **grippers, process tools, or sensors**.
- They r**ange from simple two-fingered grippers for pick-and-place tasks** to complex **sensor systems** for **robotic inspection**.
- The **3 basic types** of the end effector
  - **Grippers**
  - **Process tools**
  - **Sensors**

Robot Manipulator (End effector)

- The most common robot end effector is the humble **gripper**.
- It allows you to **pick up** and manipulate **objects**, which makes it best suited to tasks like **pick-and-place**, **assembly, and machine tending**.
- There are possibly more **different types of gripper** than there are any other type of end effector.
- By far the most popular are **fingered** grippers, which come with **2, 3, 4, or 5 fingers** — it is possible to use **6 fingers or more**, but it is rarely necessary.
- Then, there are **vacuum** grippers, **magnetic** grippers, **needle** grippers, and there are amazing new gripper technologies being developed all the time.

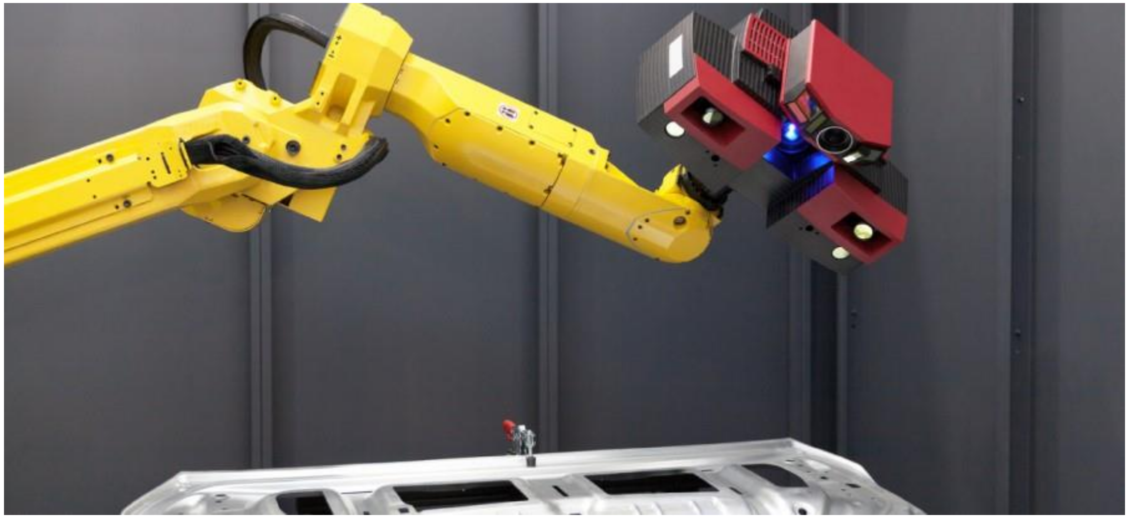

Robot Manipulator (End effector)

- A simplistic way to think of **process tools** is like a worker **operating a power tool**. While a gripper can only grasp the workpiece, a process tool **changes the workpiece**.
- There are as many **different process tools** as there are different operations in manufacturing. Examples include, robot **welding** tools, robot **machining** tools, robot **painting** tools, **3D printing** tools, and the list goes on and on.



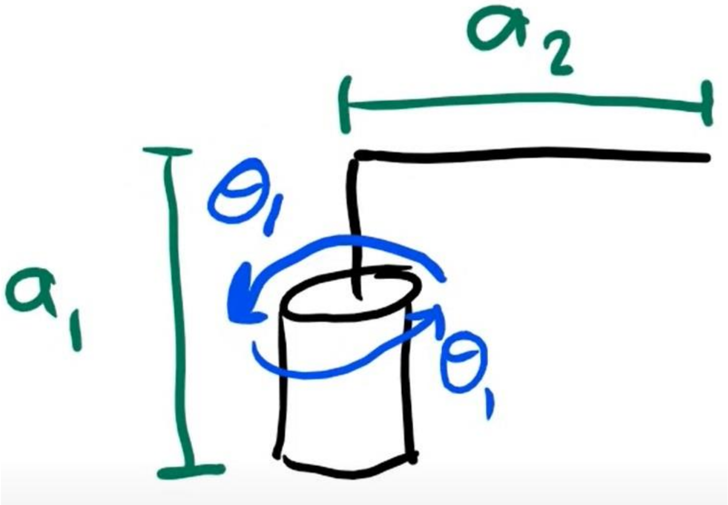
Robot Manipulator (End effector)

- You can also attach a **sensor** to use the robot as a **programmable sensor-orientation** device.
- This is particularly useful for applications like **robotic inspection** which reduces the amount of hands-on time that inspection engineers need to **spend collecting data**.
- Many sensors can serve as an end effector, including **ultrasonic** sensors, **laser scanners**, **2D and 3D cameras**, and **infrared sensors**.



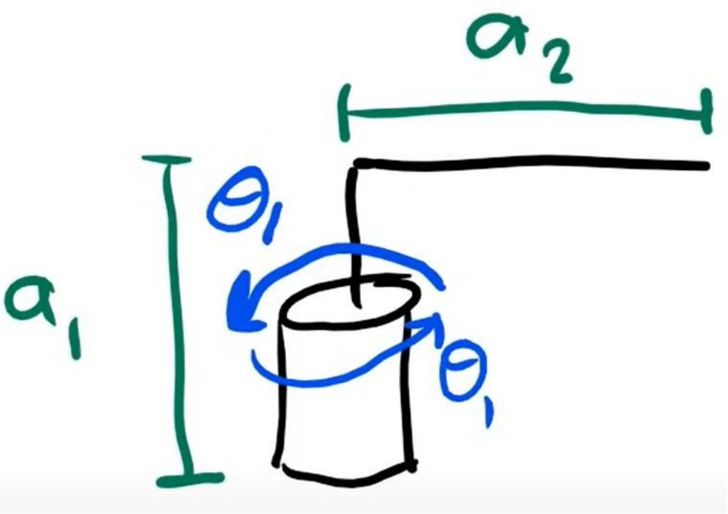

Kinematic Diagram

- A **kinematic diagram** illustrates the **connectivity of links and joints** of a mechanism or machine rather than the dimensions or shape of the parts.
- A kinematic diagram that shows how the **links and joints are connected together** when all of the **joint variables** have a **value of 0**.
- Often links are presented as **geometric objects**, such as **lines, triangles, or squares**, that support schematic versions of the joints of the mechanism or machine.
- The $\mathbf{a_1}$ and $\mathbf{a_2}$ are **links**, whereas Θ_1 is the **direction of positive rotation** of joint (determined using **RHR**).

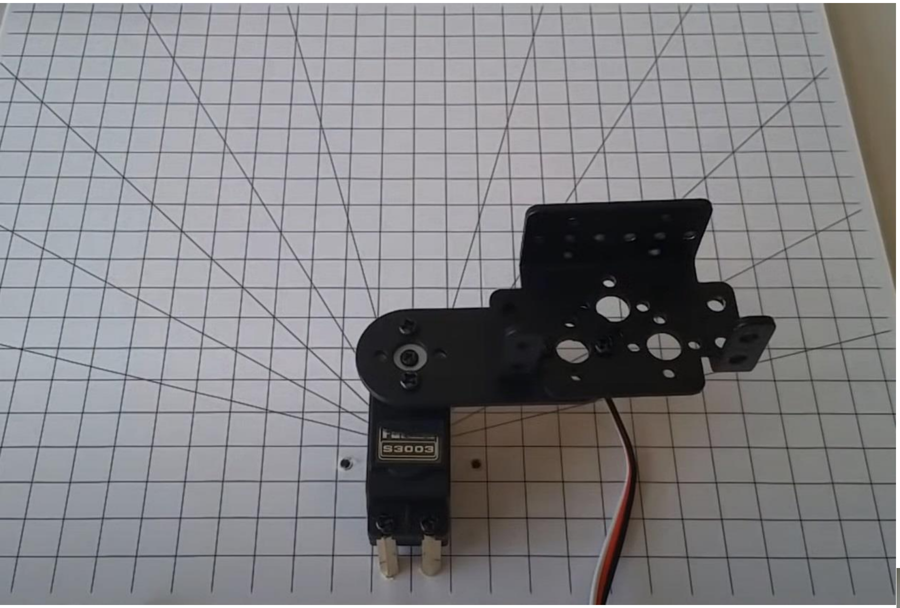


Kinematic Diagram (case 01)

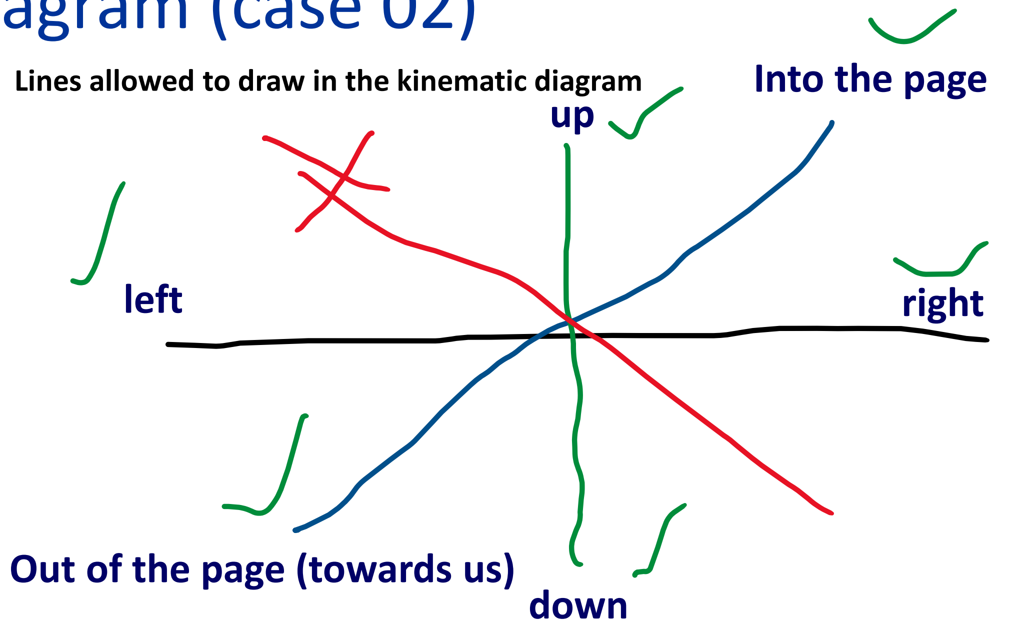
- There is **one revolute** joint and **two links a_1** and **a_2**.
- The Θ_1 is the **direction of positive rotation** of the joint.
- The direction of positive rotation is **determined** using **RHR**.

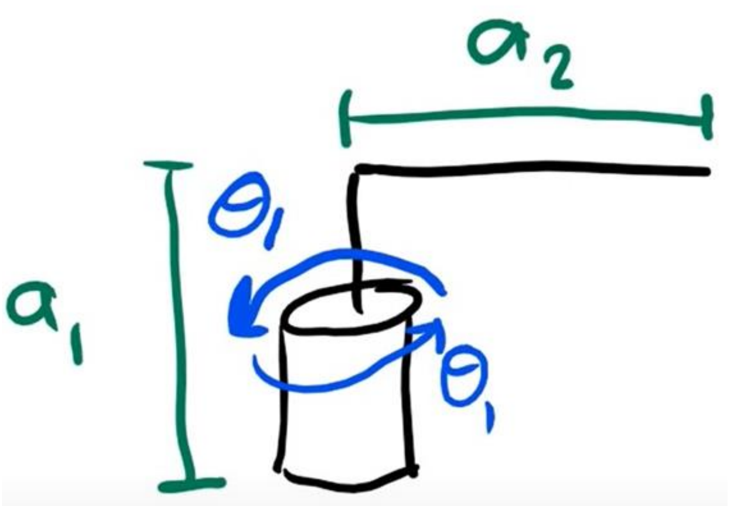


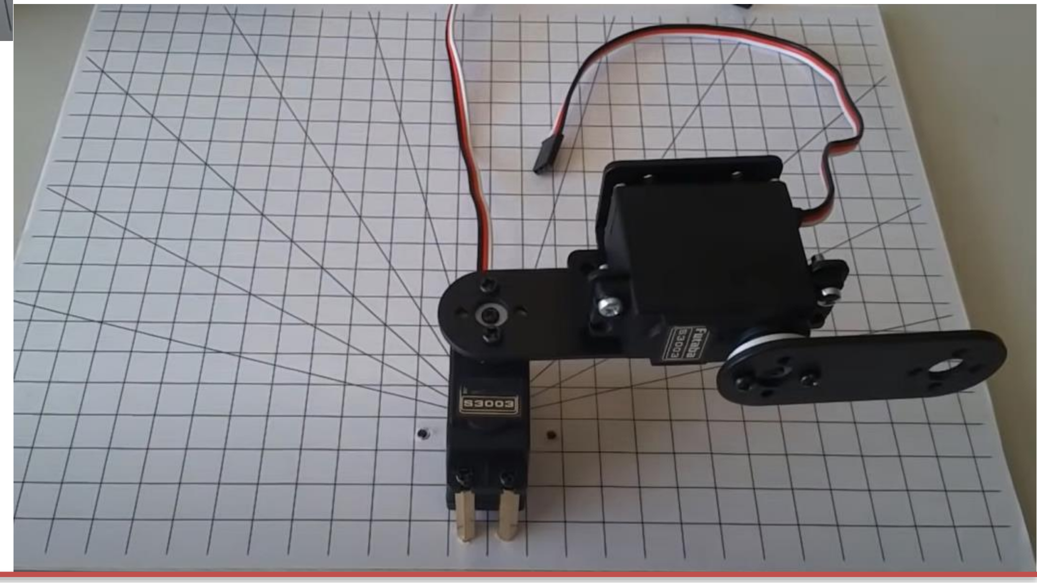
Kinematic Diagram (case 02)



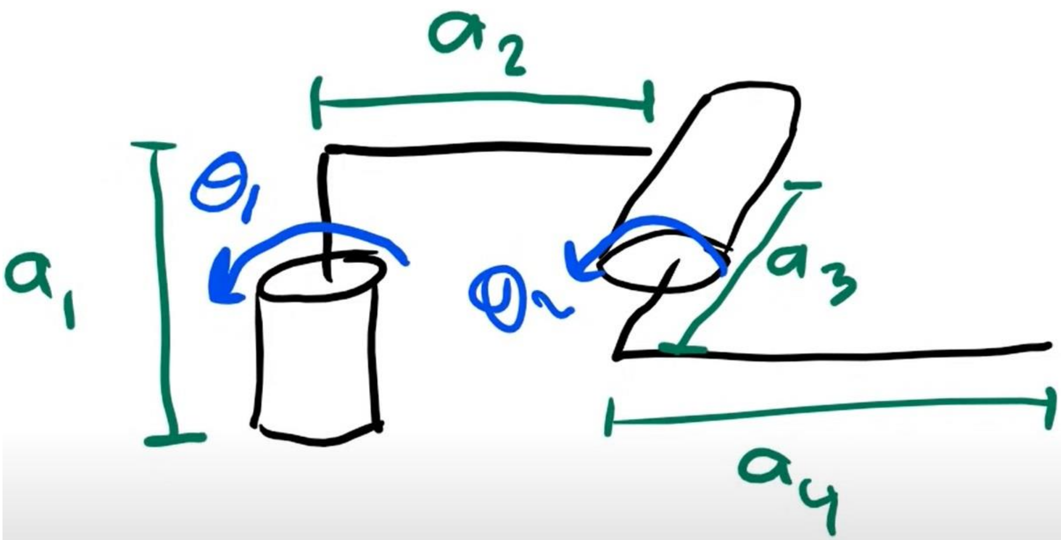
Lines allowed to draw in the kinematic diagram



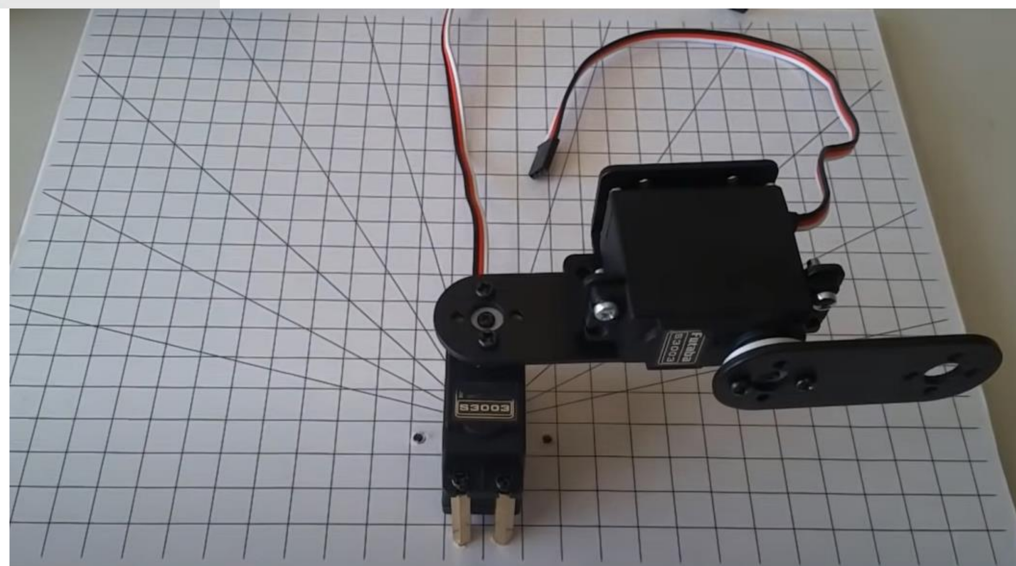




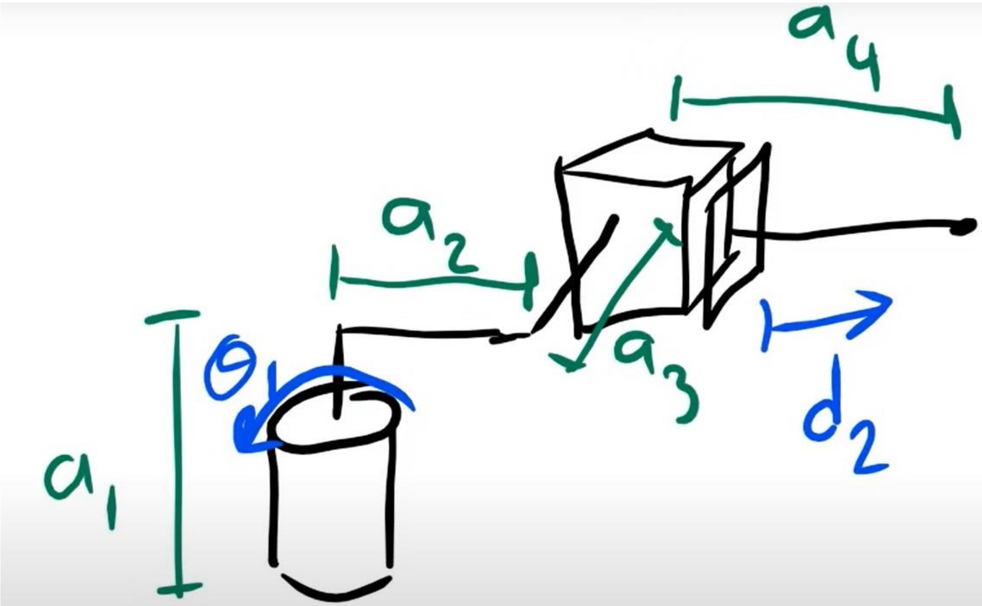
Kinematic Diagram (case 02)



- It has **two revolute joints** with positive rotations of $\boldsymbol{\Theta_1}$ and $\boldsymbol{\Theta_2}$.
- It has **four links a$_1$, a$_2$, a$_3$,** and **a$_4$**.

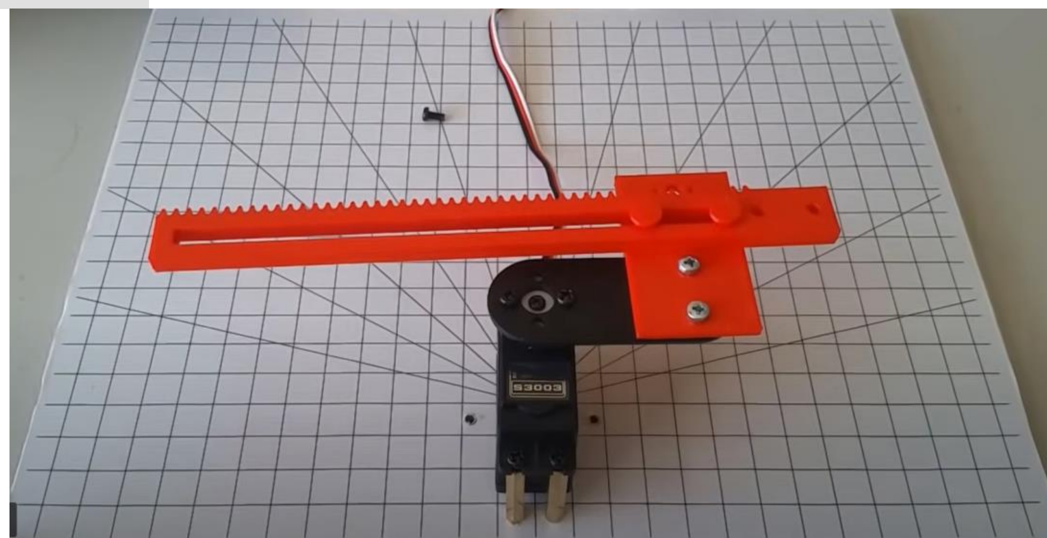


Kinematic Diagram (case 03)

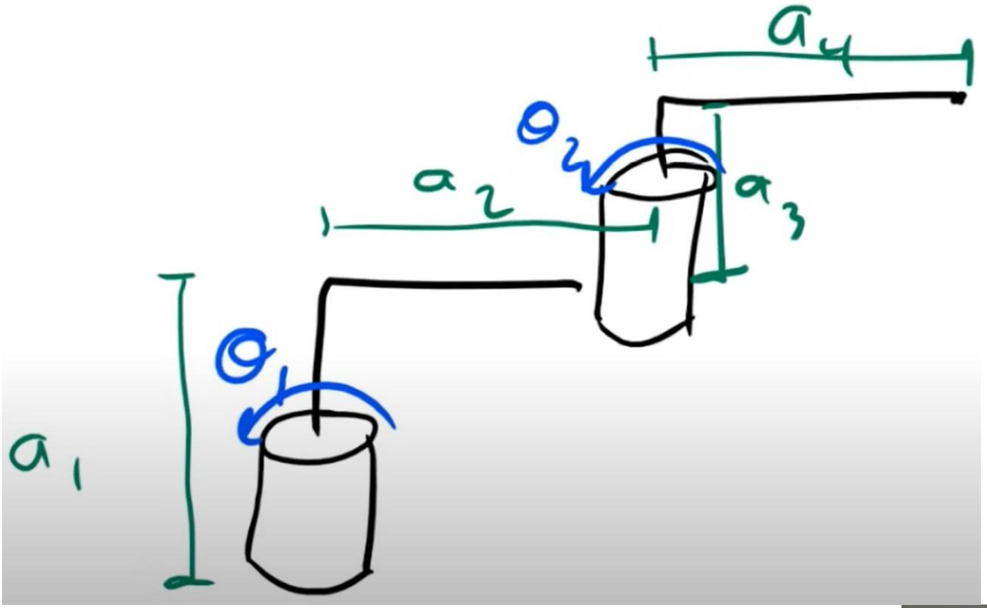


- This manipulator has **four links** $\mathbf{a_1}$, $\mathbf{a_2}$, $\mathbf{a_3}$, and $\mathbf{a_4}$.
- It has **one revolute joint** and **one prismatic joint**.
- The revolute joint has $\boldsymbol{\Theta_1}$ positive rotation, whereas the prismatic joint's **positive displacement** is $\mathbf{d_2}$.

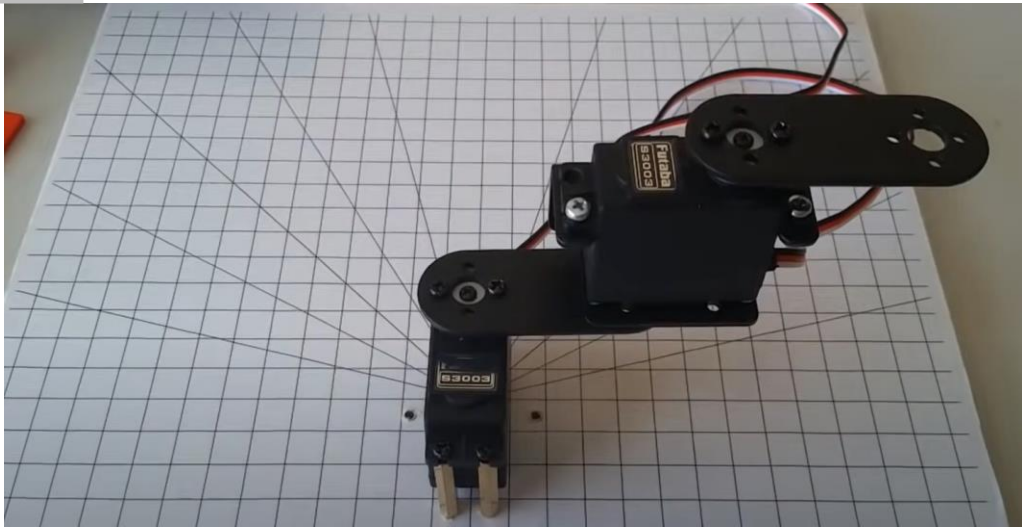
- Here, $\boldsymbol{\Theta}$ and $\mathbf{d}$ are **joint variables**.
- **Joint variable value** changes when a **joint perform movement**.
- The $\boldsymbol{\Theta_1}$ was the **first joint variable**, whereas $\mathbf{d_2}$ was the **second joint variable**.
- The **positive direction** of prismatic **displacement** is on the **right side**.



Kinematic Diagram (case 04)



- This manipulator has **four links** $\mathbf{a_1}$, $\mathbf{a_2}$, $\mathbf{a_3}$, and $\mathbf{a_4}$.
- It has **two revolute** joints.
- The revolute joints have $\mathbf{\Theta_1}$ and $\mathbf{\Theta_2}$ positive direction of rotations.



Coordinate Frame

- A **Cartesian coordinate frame** consist of **x**, **y** and **z** axis.
- In order to drive equations from **kinematic diagrams**, we need coordinate frames.
- We need at least **one coordinate frame** as a **base** frame, the frame that represents **real-world** or the **ground** to which the robot is attached.
- We need **one frame** for the **end effector** of the robot.
- To **draw frames on the kinematic diagrams**, we **need** to follow **four rules** known as the "**Denavit-Hartenberg**" rules.

Denavit-Hartenberg Rules

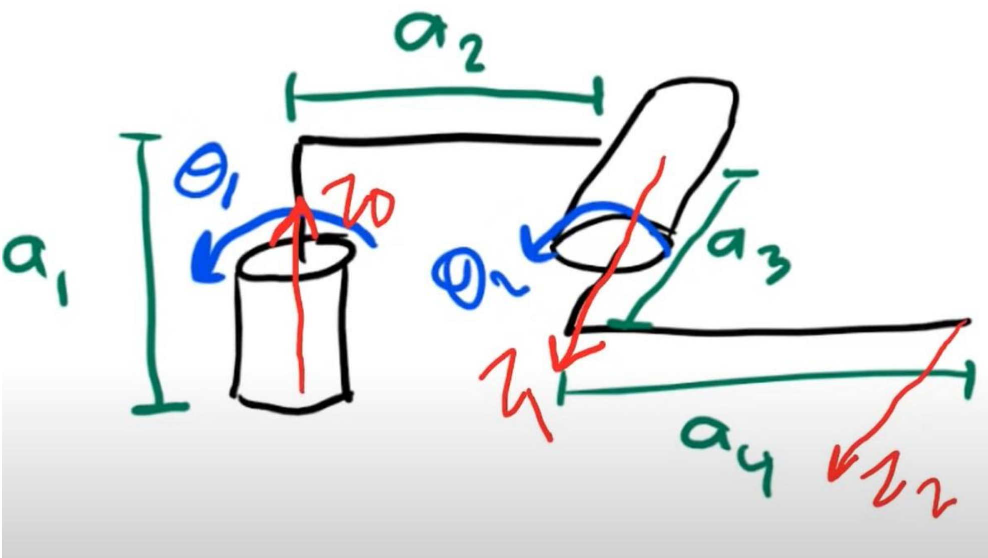
- **Rule # 01**: The **z-axis** must be the **axis of rotation** for a **revolute joint** or the **direction of motion** for a **prismatic joint**.

- **Rule # 02**: The **x-axis** must be **perpendicular** both to its **own z-axis**, and the **z-axis** for the frame **before** it.

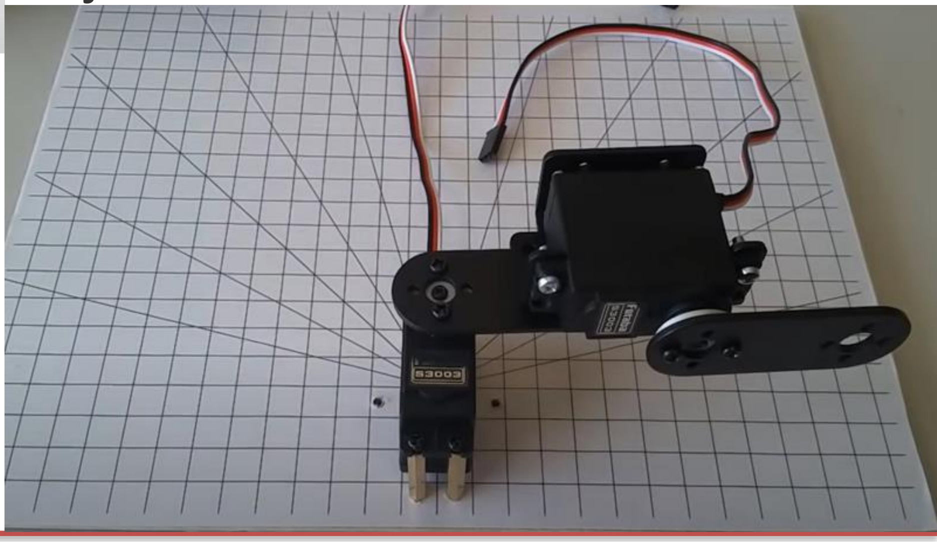
- **Rule # 03**: **All frames** must **follow** the **right-hand rule**.

- **Rule # 04**: **Each x-axis** must **intersect** the **z-axis** of the frame **before** it (this rule doesn't apply to frame 0 as there is no frame before it).

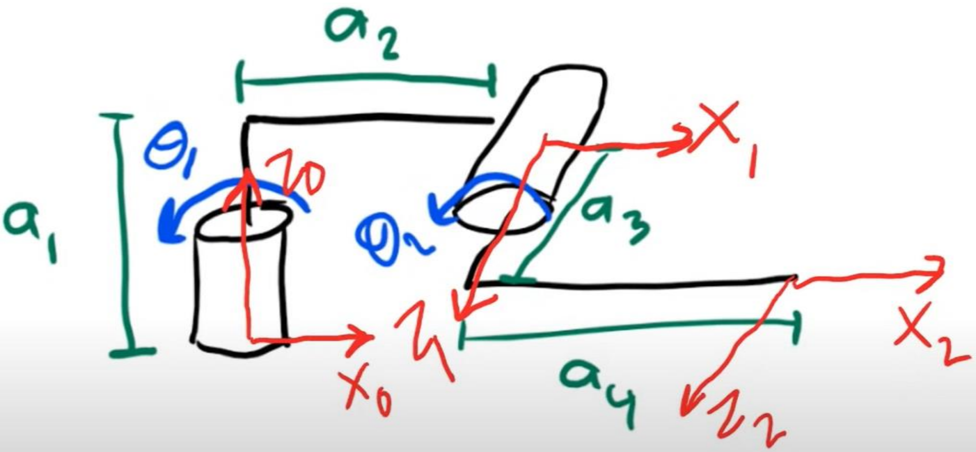
Rule # 01 (case 01)



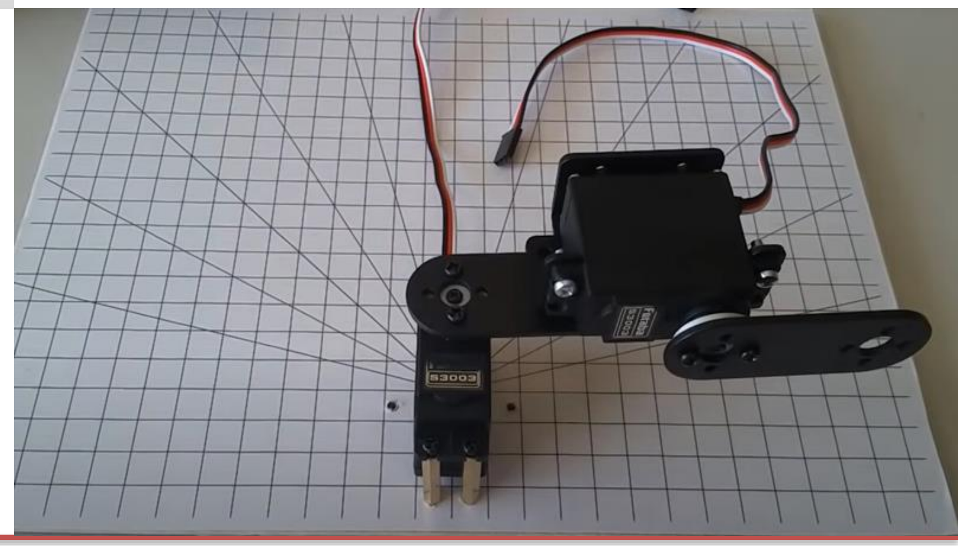
- **Rule # 01**: The **z-axis** must be the **axis of rotation** for a **revolute joint** or the **direction of motion** for a **prismatic joint**.
- As there is **no axis of rotation** on **end effector**, for this reason it will follow the z-axis of **previous joint.**



Rule # 02 (case 01)

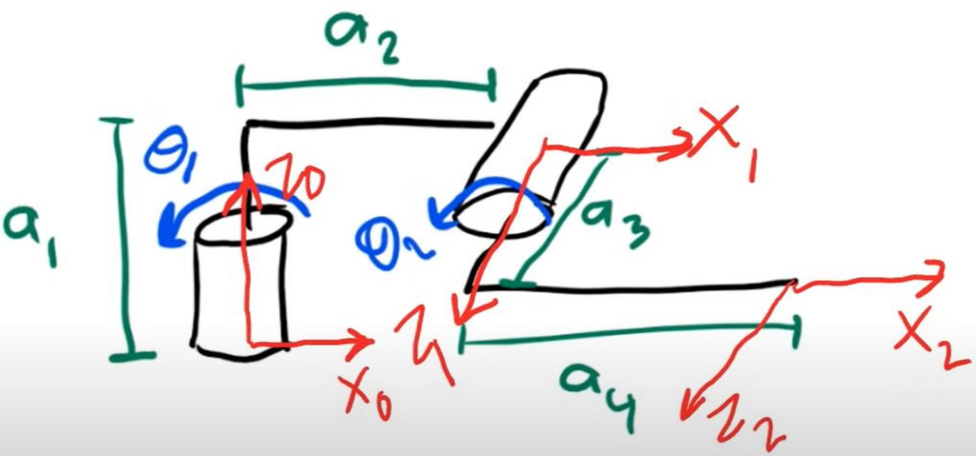


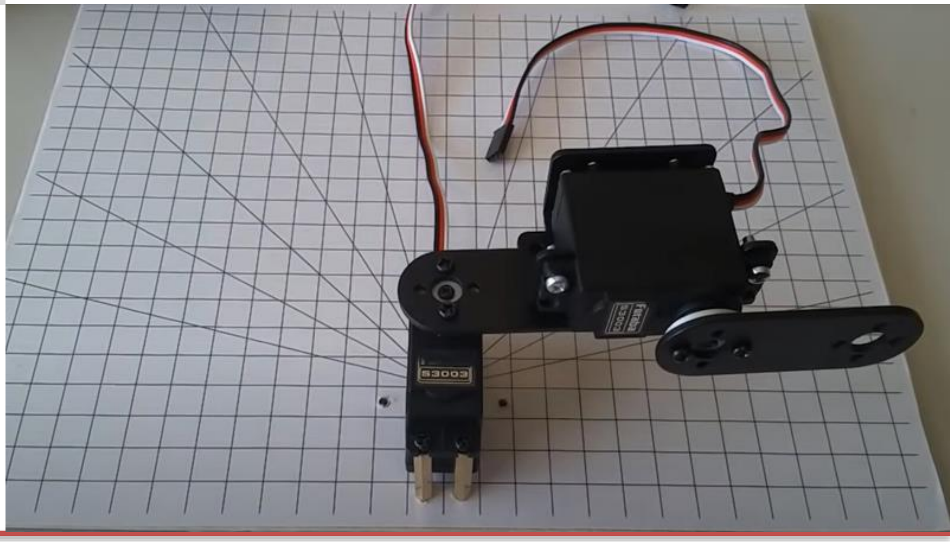
- **Rule # 02**: The **x-axis** must be **perpendicular** both to its **own z-axis**, and the **z-axis** for the frame **before** it.
- X_1 cannot be **into or out of the page** to be perpendicular to both z-axes.



Rule # 03 (case 01)

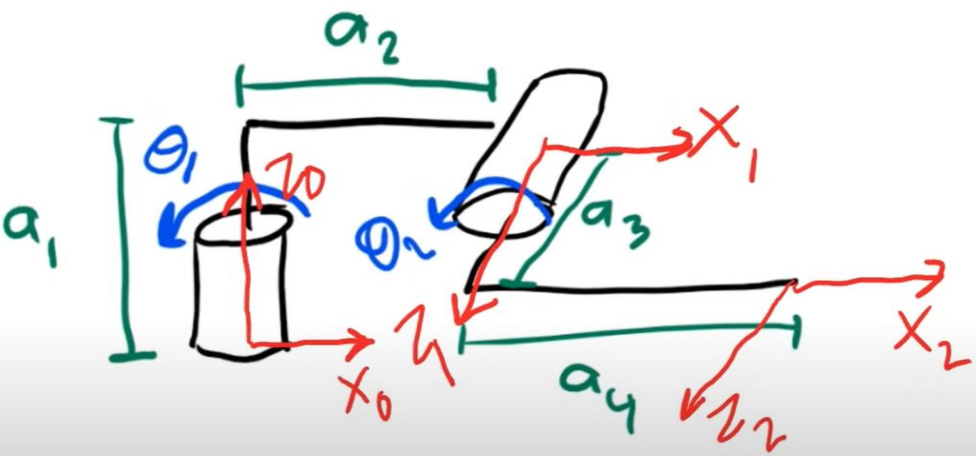
- **Rule # 03**: **All frames** must **follow** the **right-hand rule**.

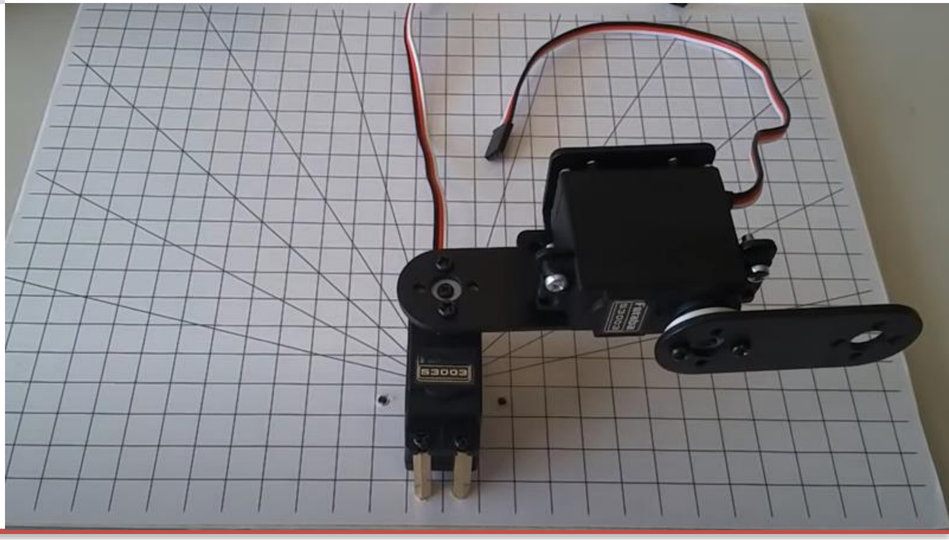




Rule # 03 (case 01)

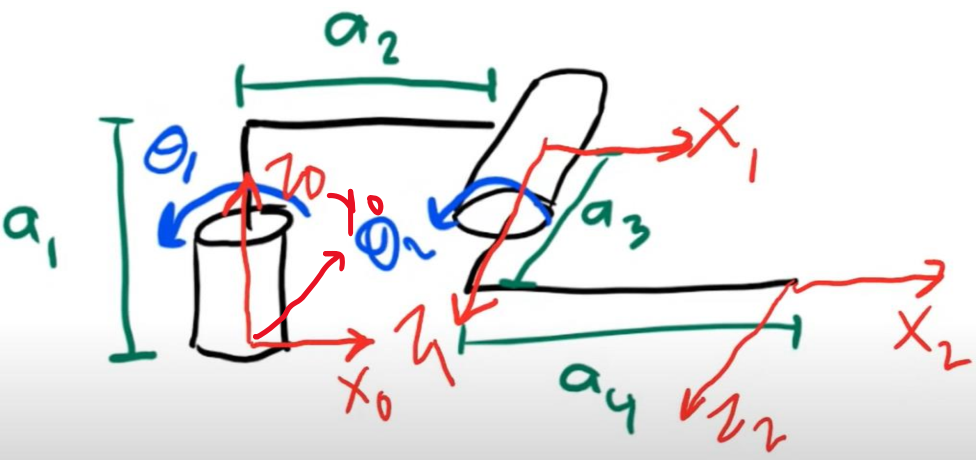
- **Rule # 03**: **All frames** must **follow** the **right-hand rule**.

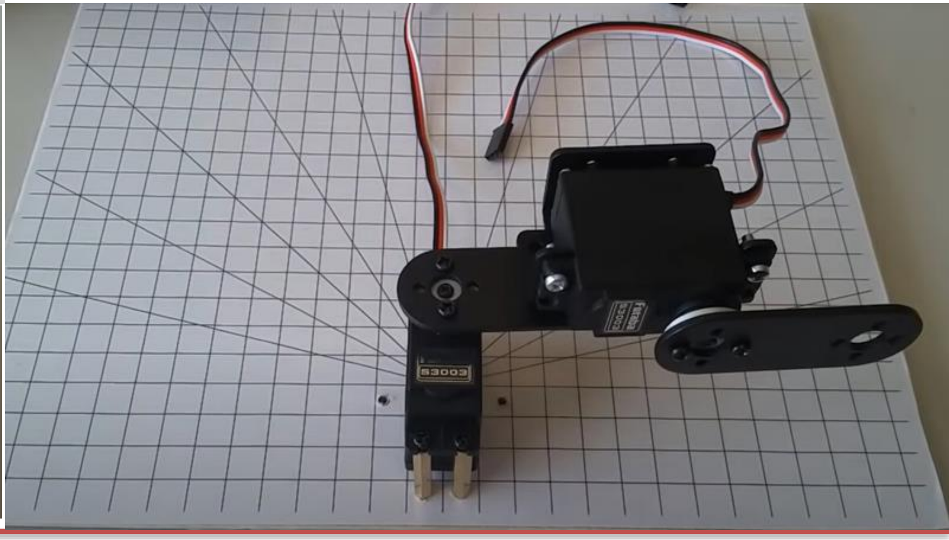




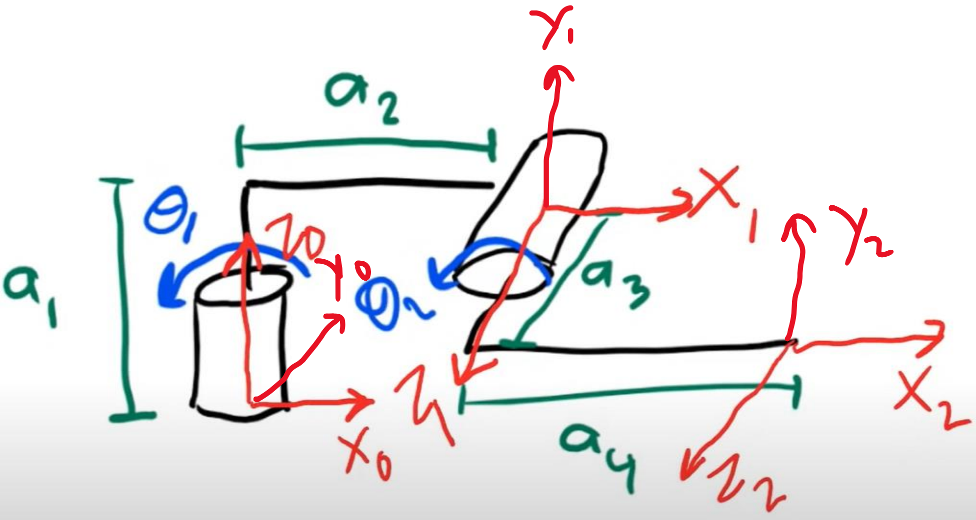
Rule # 03 (case 01)

- **Rule # 03**: **All frames** must **follow** the **right-hand rule**.
- **Frame 0**

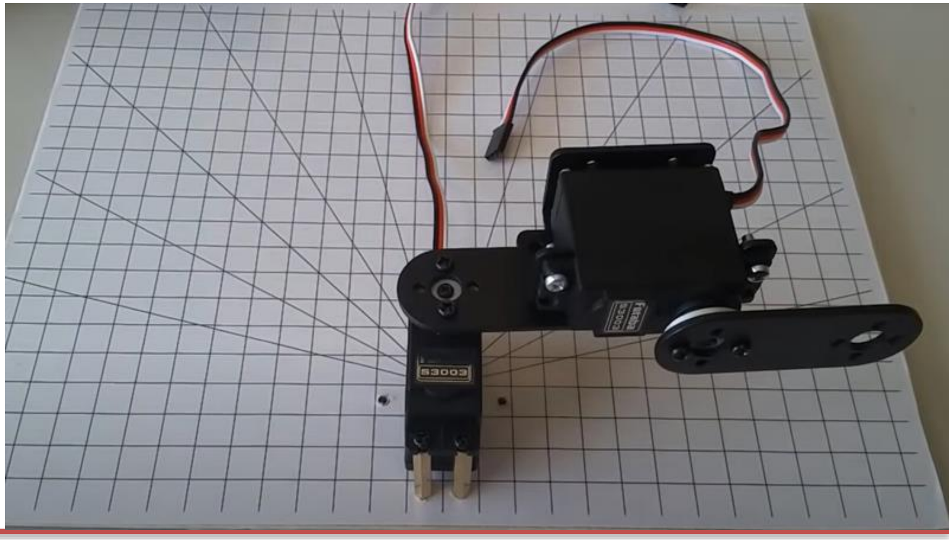




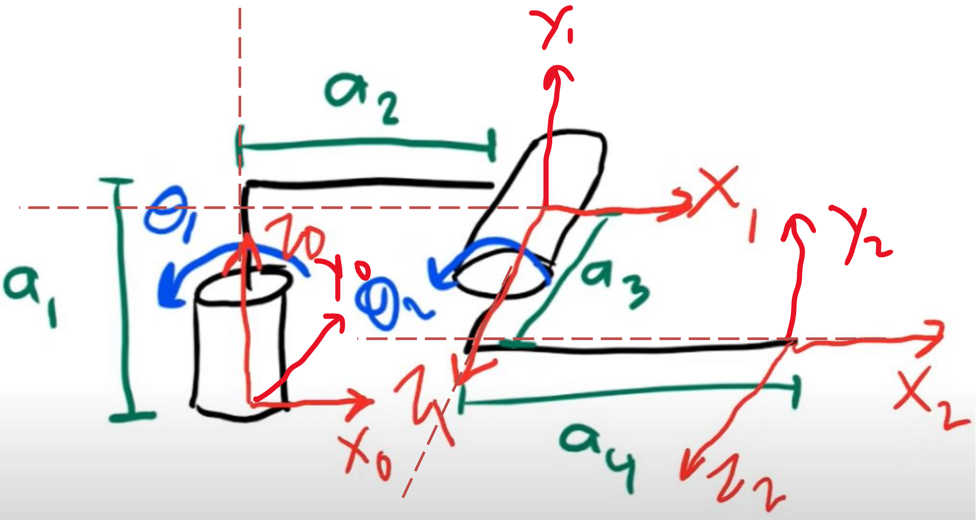
Rule # 03 (case 01)



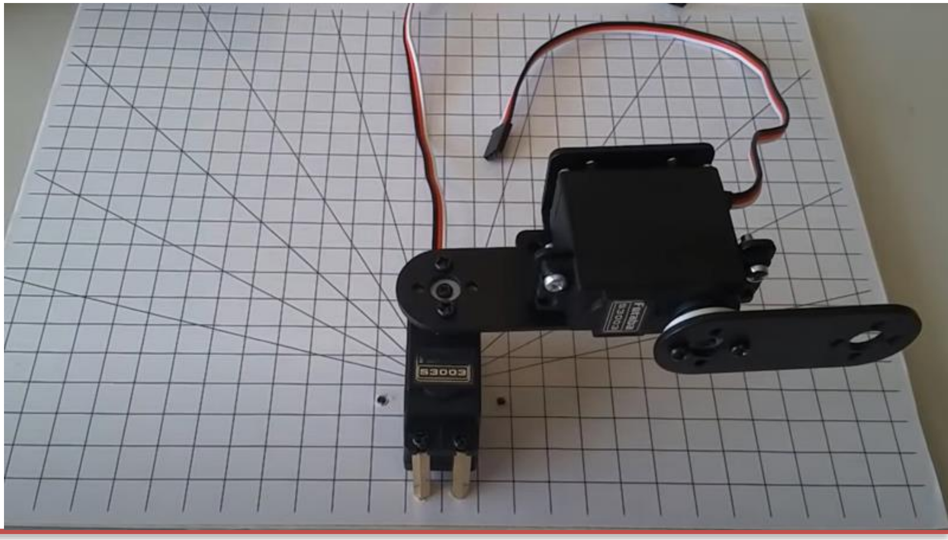
- **Rule # 03**: **All frames** must **follow** the **right-hand rule**.
- **Frame 1** and **Frame 2**



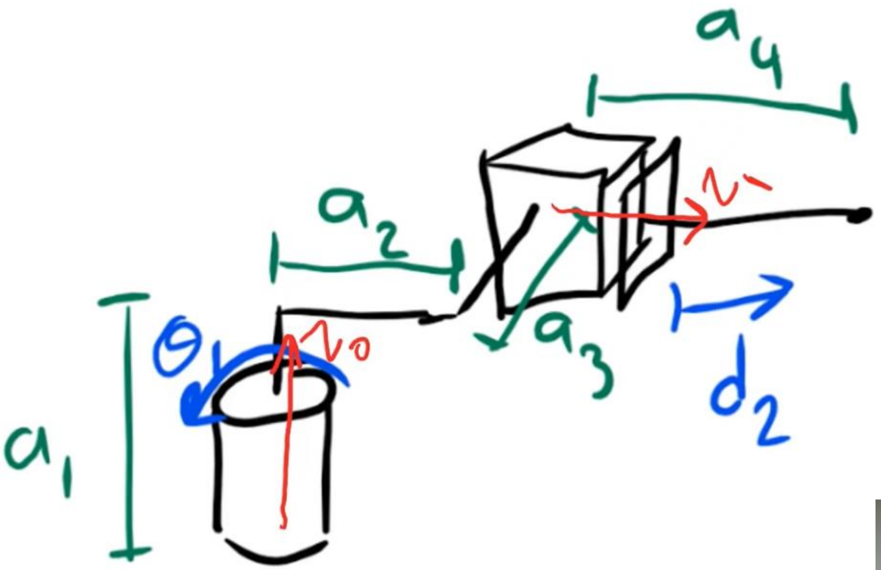
Rule # 04 (case 01)



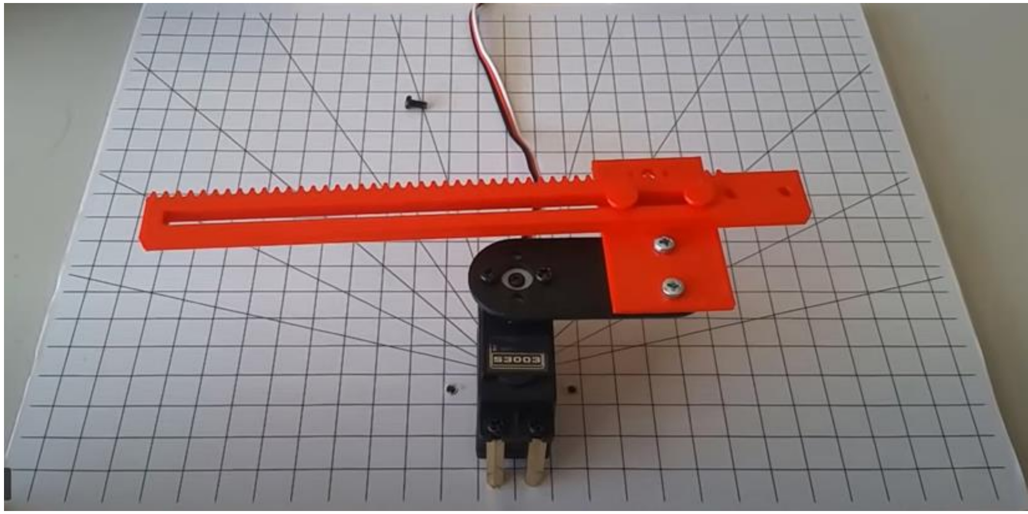
- **Rule # 04**: **Each x-axis** must **intersect** the **z-axis** of the frame **before** it (this rule doesn't apply to frame 0 as there is no frame before it).
- For **Frame 0** and **Frame 1**
- All rules **ok** for this kinematic diagram.



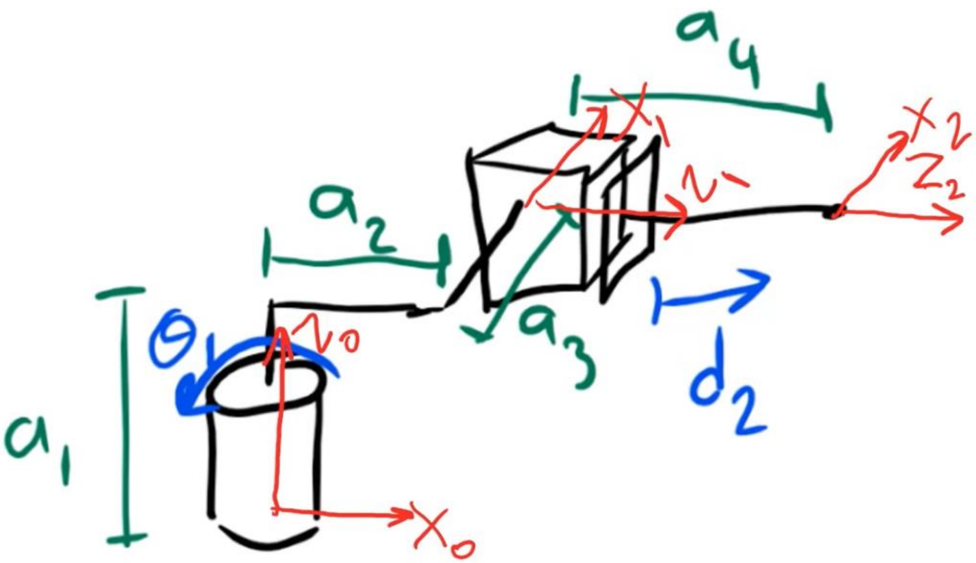
Rule # 01 (case 02)



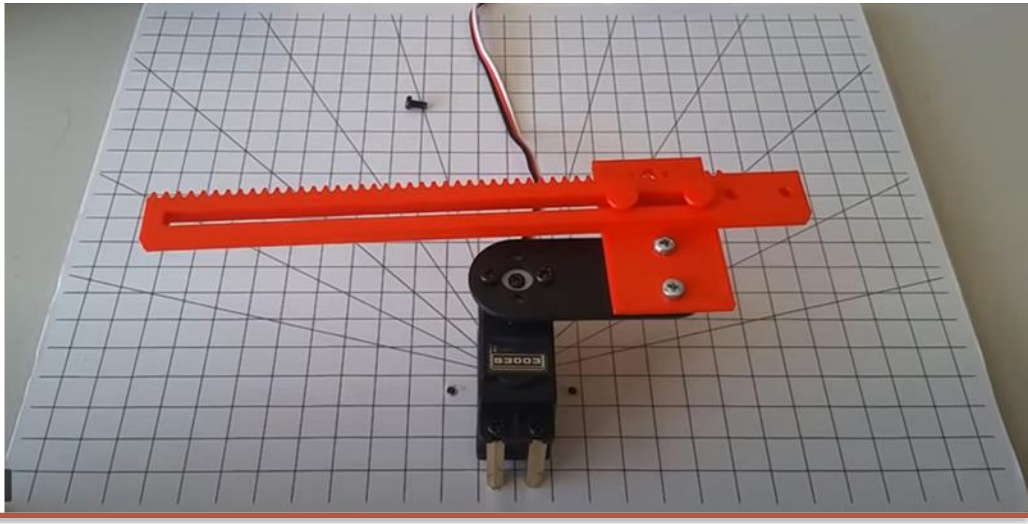
- **Rule # 01**: The **z-axis** must be the **axis of rotation** for a **revolute joint** or the **direction of motion** for a **prismatic joint**.



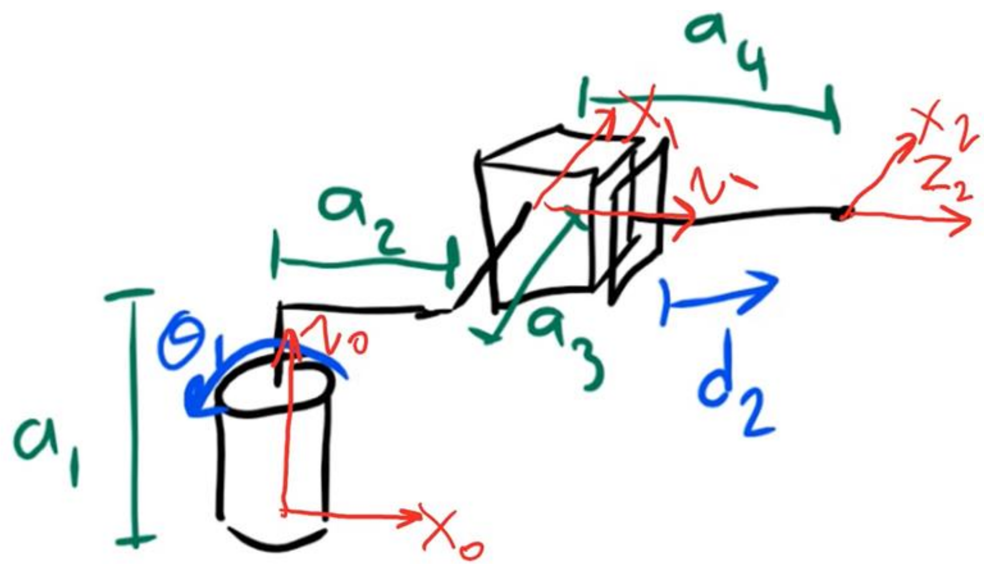
Rule # 02 (case 02)



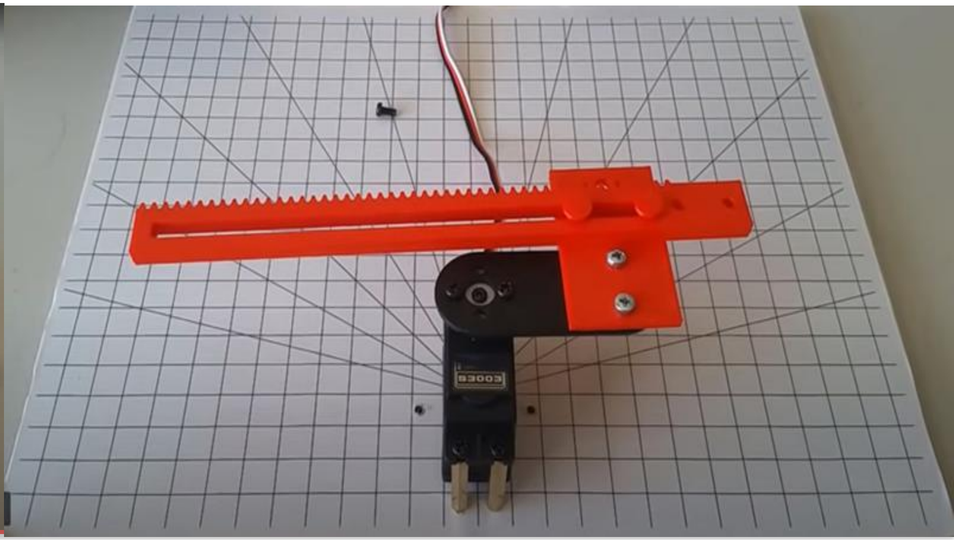
- **Rule # 02**: The **x-axis** must be **perpendicular** both to its **own z-axis**, and the **z-axis** for the frame **before** it.
- X_1 cannot be **up or down** in **the page** to be perpendicular to Z_0.



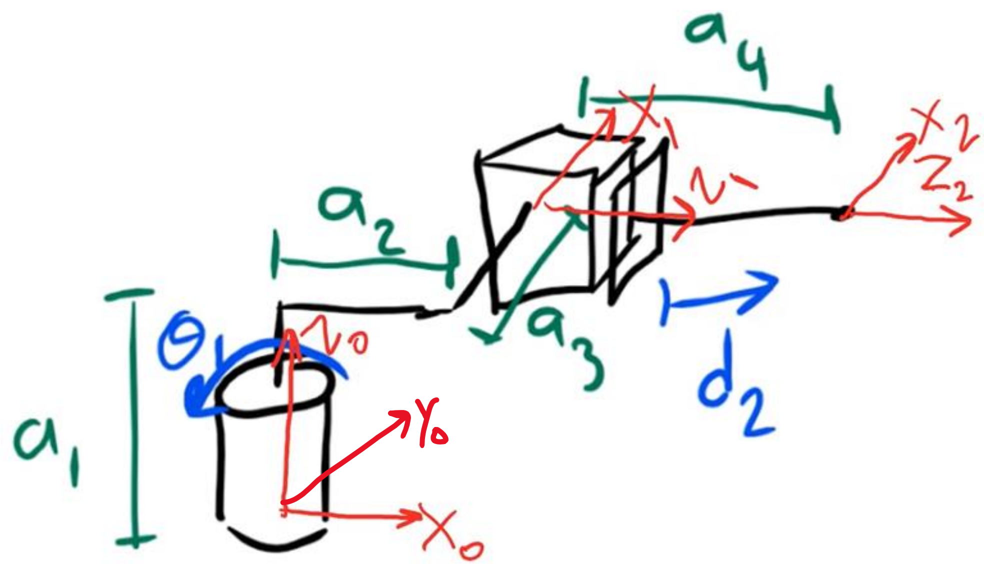
Rule # 03 (case 02)



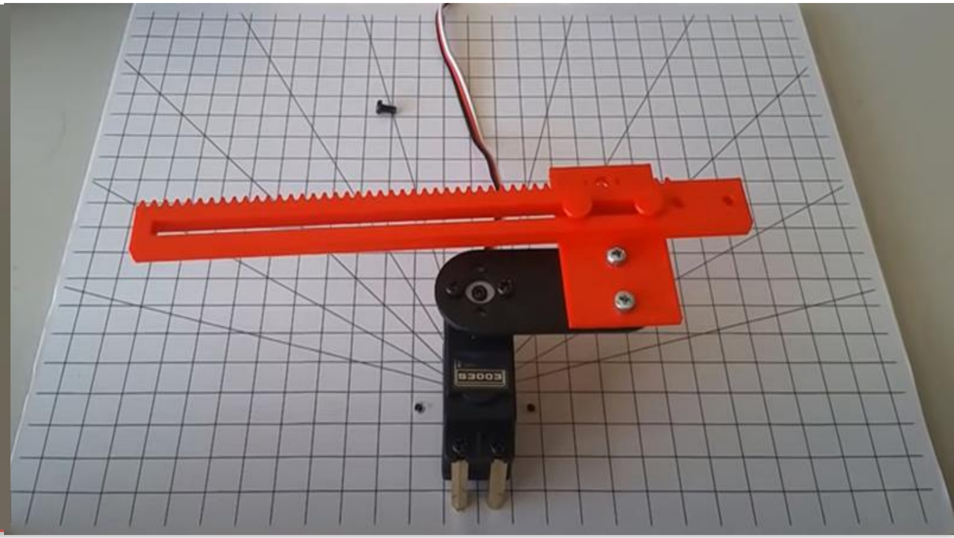
- **Rule # 03**: **All frames** must **follow** the **right-hand rule**.



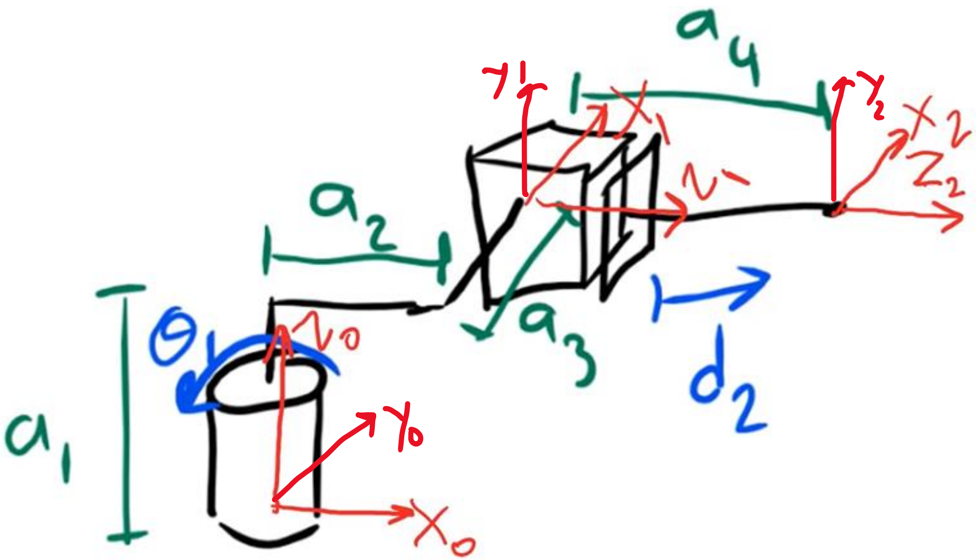
Rule # 03 (case 02)



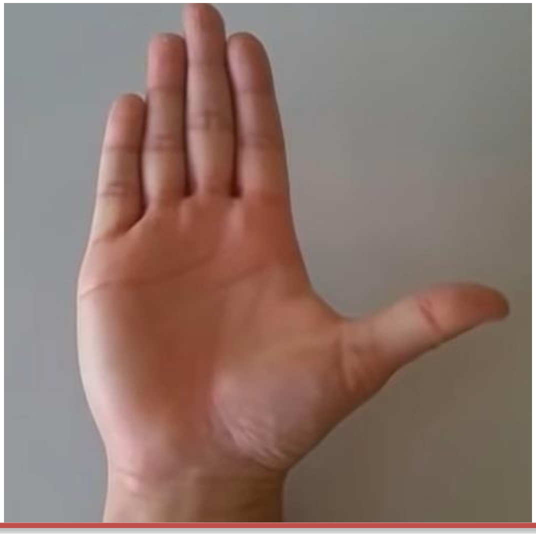
- **Rule # 03**: **All frames** must **follow** the **right-hand rule**.

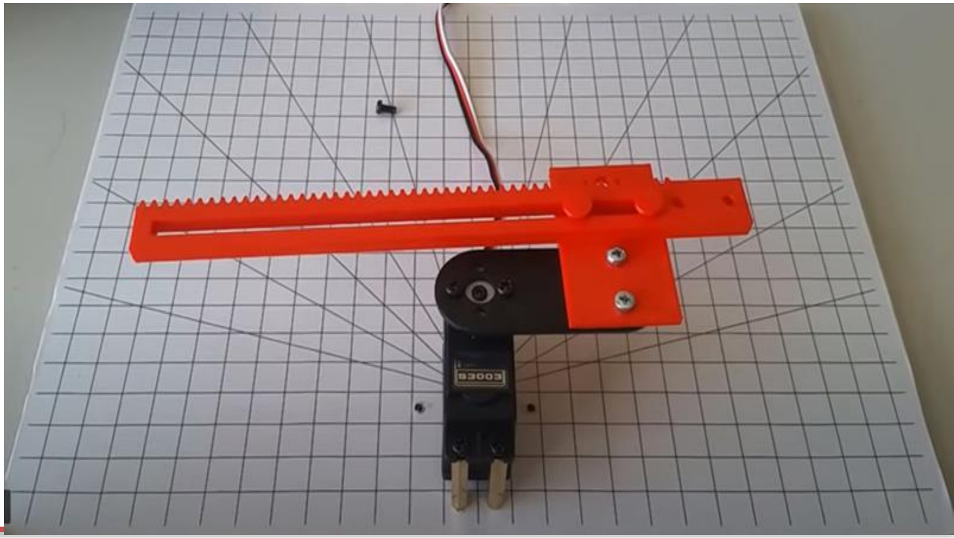


Rule # 03 (case 02)

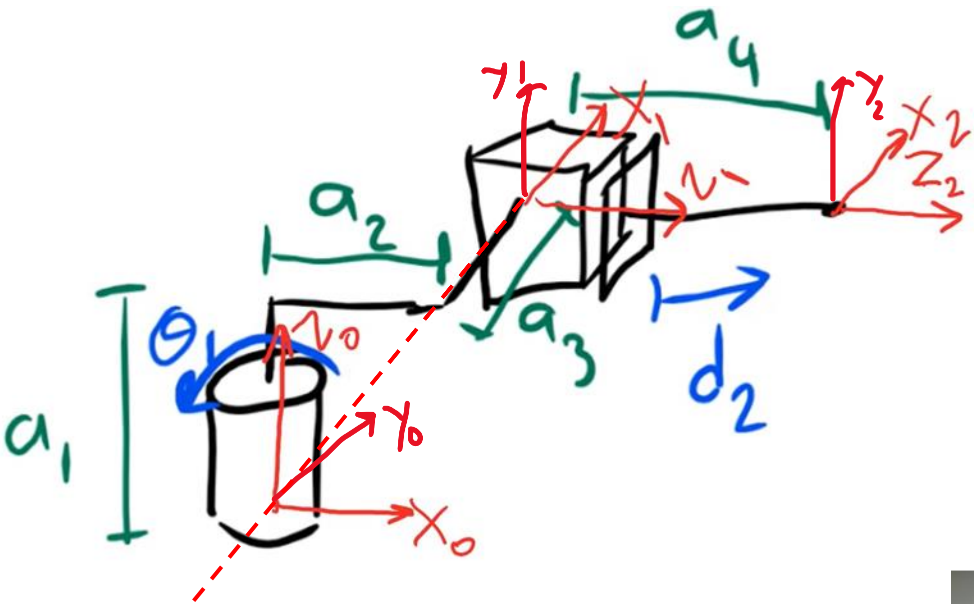


- **Rule # 03**: **All frames** must **follow** the **right-hand rule**.

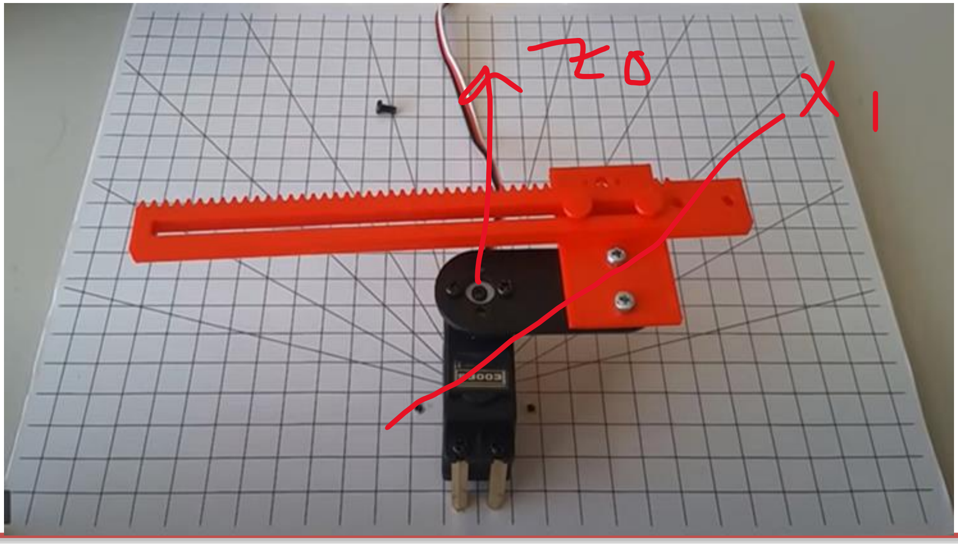




Rule # 04 (case 02)

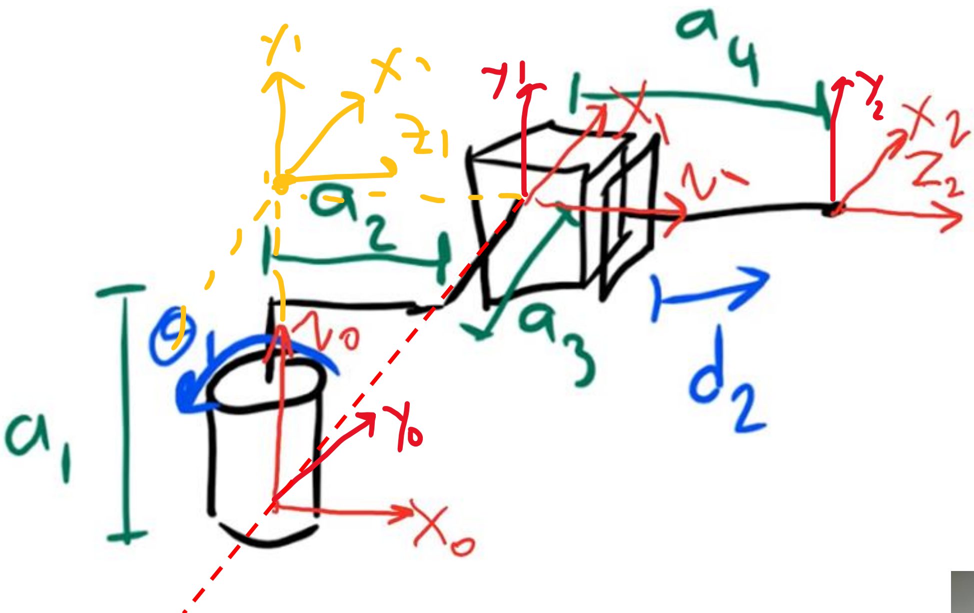


- **Rule # 04**: **Each x-axis** must **intersect** the **z-axis** of the frame **before** it (this rule doesn't apply to **frame 0** as there is no frame before it).
- The $\mathbf{X_1}$ is not intersecting $\mathbf{Z_0}$
- We need to move the center of **Frame1** to the **left side**.
- If you look at $\mathbf{X_1}$ in **3D** space, then you see $\mathbf{X_1}$ **pass by** $\mathbf{Z_0}$



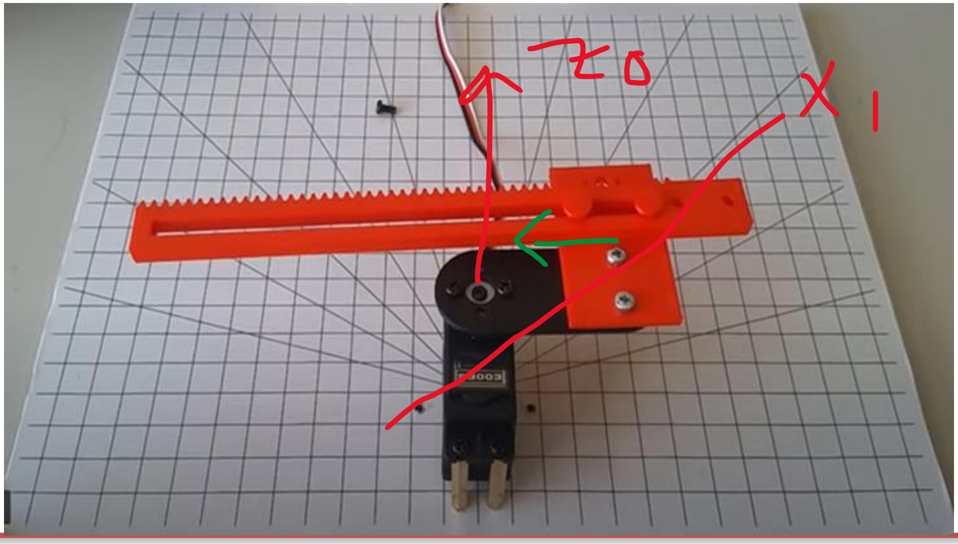
- The $\mathbf{X_1}$ is not intersecting $\mathbf{Z_0}$
- Till now, we have put each frame at the **center of each joint**, that is a good practice.
- However, it is **not a mandatory** condition. You can **move** the center **to your required position.**

Rule # 04 (case 02)

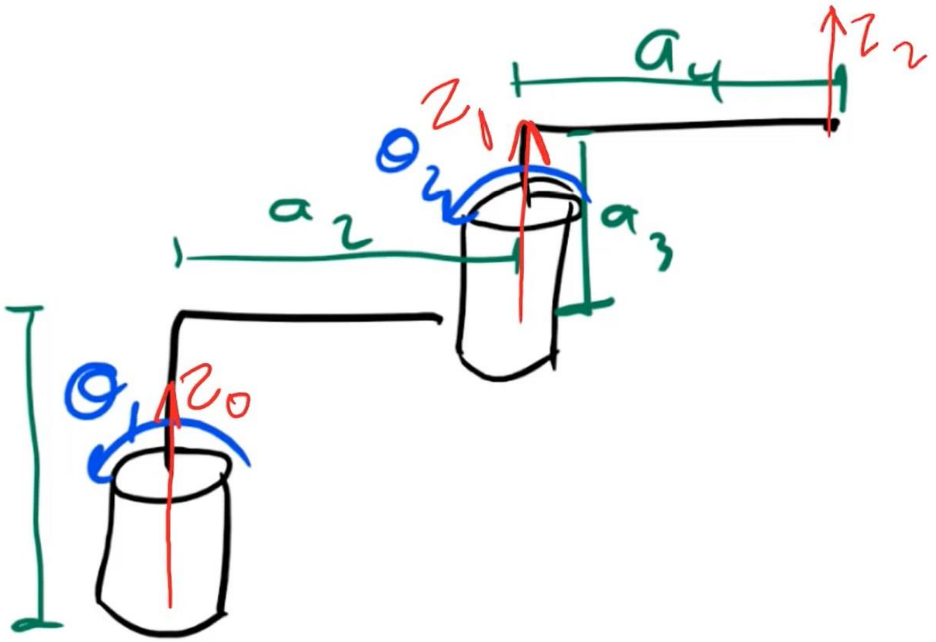


- The X_1 **is on the right side of** Z_0. Therefore, we need to move **Frame 1** center to the left.
- The minimum left position where X_1 **will intersect** Z_0 is a_2 distance to the left.
- Now, X_1 will intersect Z_0 at the center of **Frame 1.**

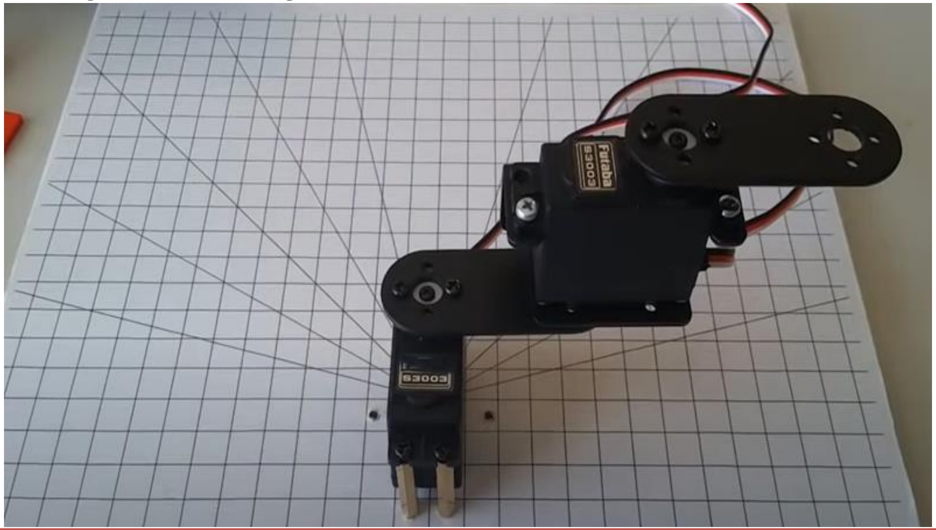
- **Move Frame 1 to the left**
- For **Frame 0** and **Frame 1**
- After **modification**, all rules **ok** for this kinematic diagram.



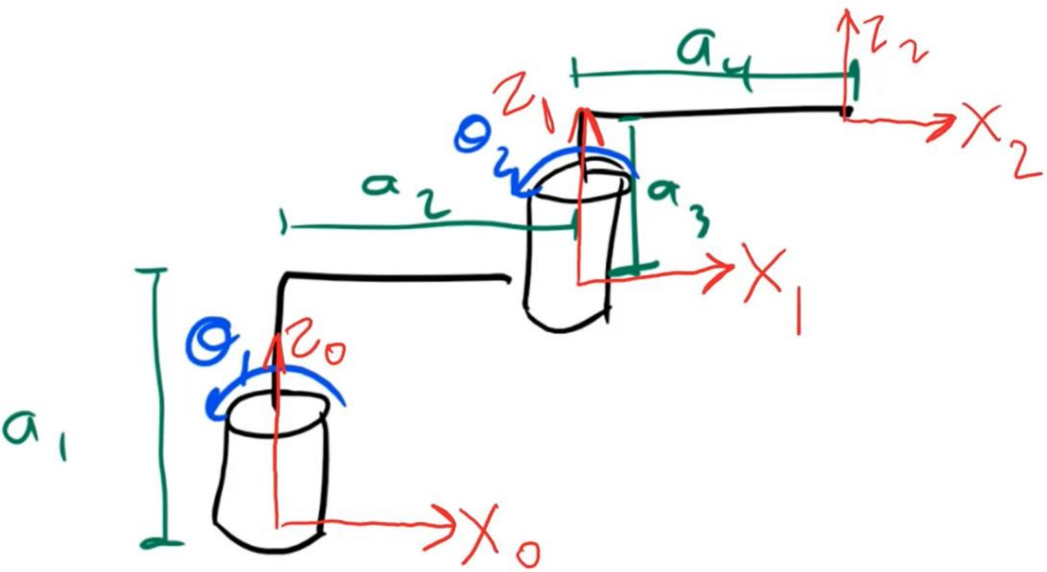
Rule # 01 (case 03)



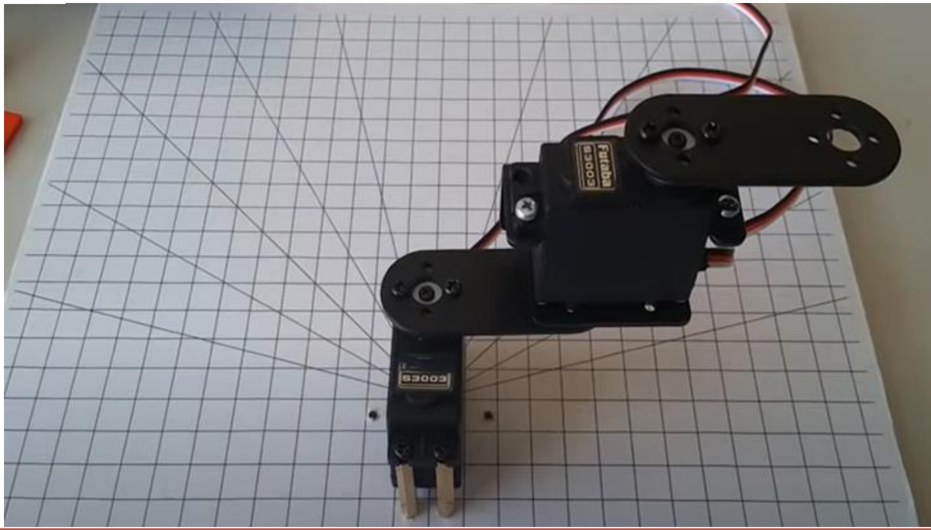
- **Rule # 01**: The **z-axis** must be the **axis of rotation** for a **revolute joint** or the **direction of motion** for a **prismatic joint**.
- As there is **no axis of rotation** on the **end effector**, for this reason, it will follow the z-axis of the **previous joint.**



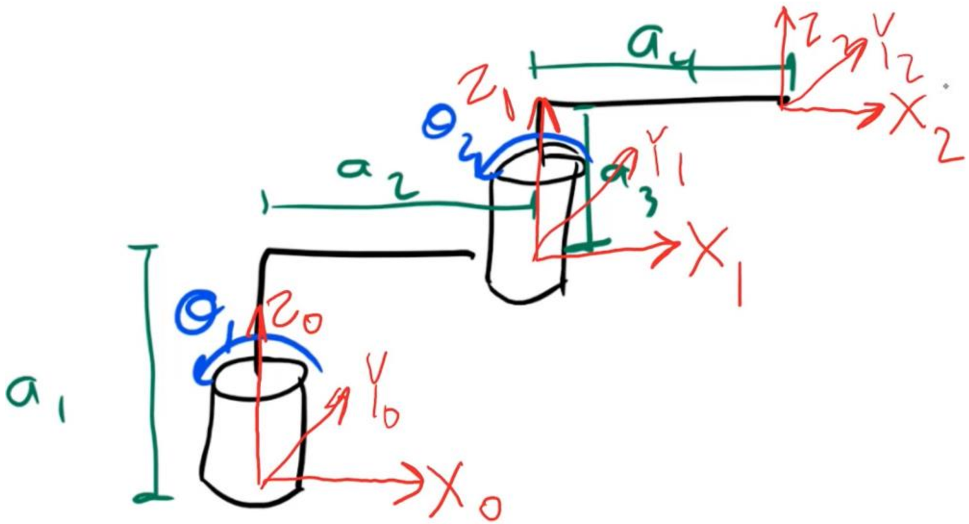
Rule # 02 (case 03)



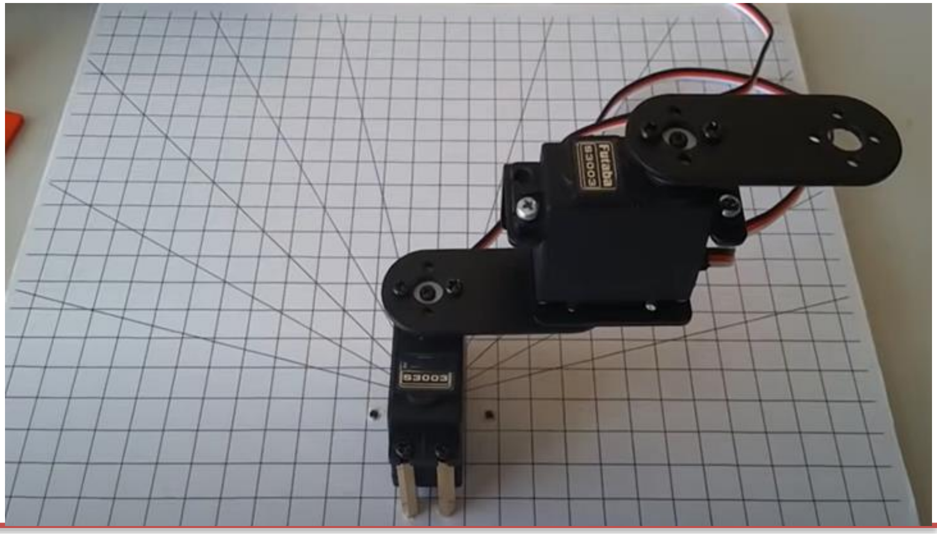
Rule # 02: The **x-axis** must be **perpendicular** both to its **own z-axis**, and the **z-axis** for the frame **before** it.



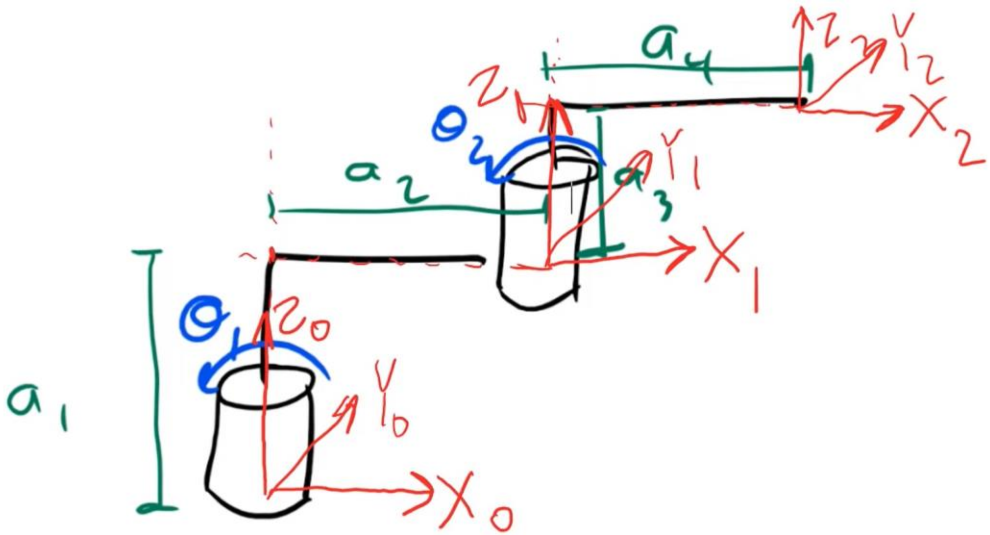
Rule # 03 (case 03)



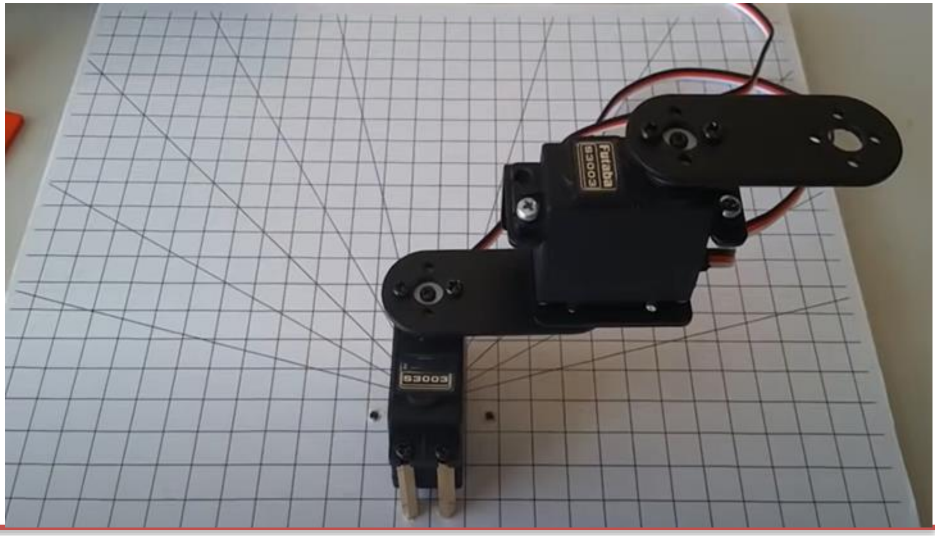
- **Rule # 03**: **All frames** must **follow** the **right-hand rule**.
- **Frame 0, 1,** and **2** would follow **RHR** in the same way.



Rule # 04 (case 03)



- **Rule # 04**: **Each x-axis** must **intersect** the **z-axis** of the frame **before** it (this rule doesn't apply to frame 0 as there is no frame before it).
- No need of modification in frames.
- All rules **ok** for this kinematic

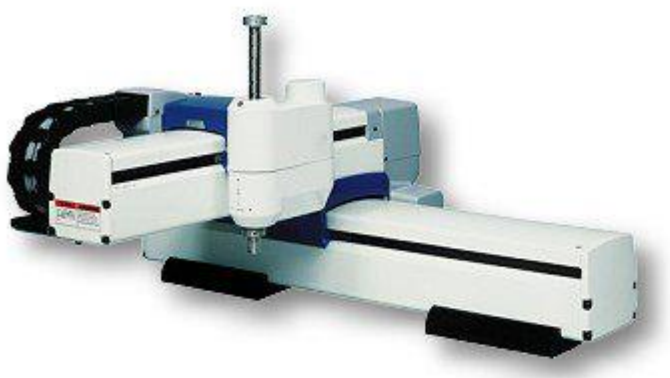


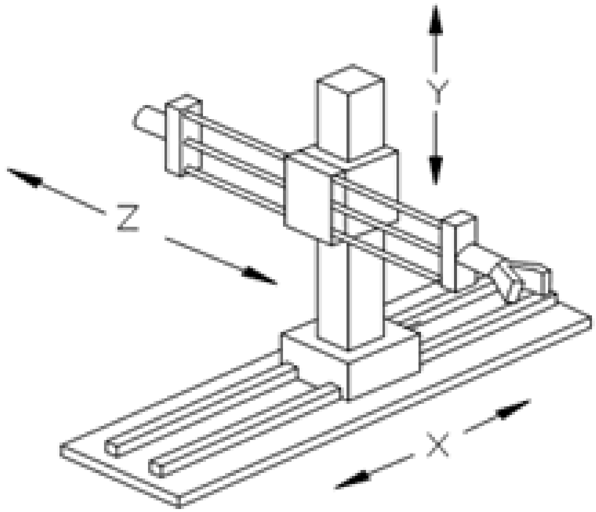
3 DoF Manipulators

- To help you solidify your understanding and build your skills with **kinematic diagrams**, we give you five examples of **drawing Denavit-Hartenberg frames on 3-DoF** manipulators.
- The five examples cover the **five 'standard manipulator types'**:
  - **Cartesian**
  - **Articulated**
  - **SCARA**
  - **Spherical**
  - **Cylindrical**

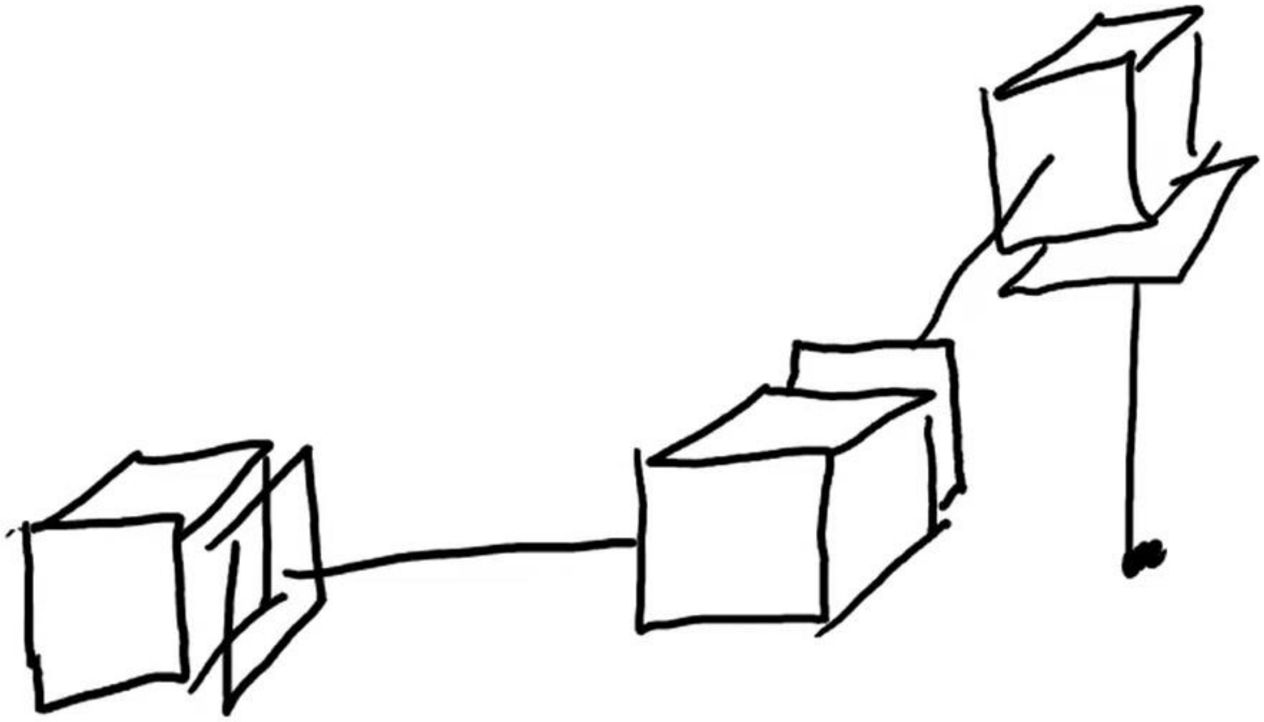
Cartesian Manipulator

- **Cartesian robots**, which are also called **linear robots**, are **industrial** robots that work on **three linear axes** that use the **Cartesian Coordinate system** (**X**, **Y**, and **Z**).
- They move in straight lines on **3-axis** (**up** and **down**, **in** and **out**, and **side to side**).
- Cartesian robots are a popular choice due to being highly **flexible** in their configurations, giving users the ability to adjust the robot's **speed**, **precision**, **stroke** length, and **size**.
- Cartesian Robots are one of the most commonly used robot types for **industrial applications** and are often used for **CNC machines** and **3D printing**.

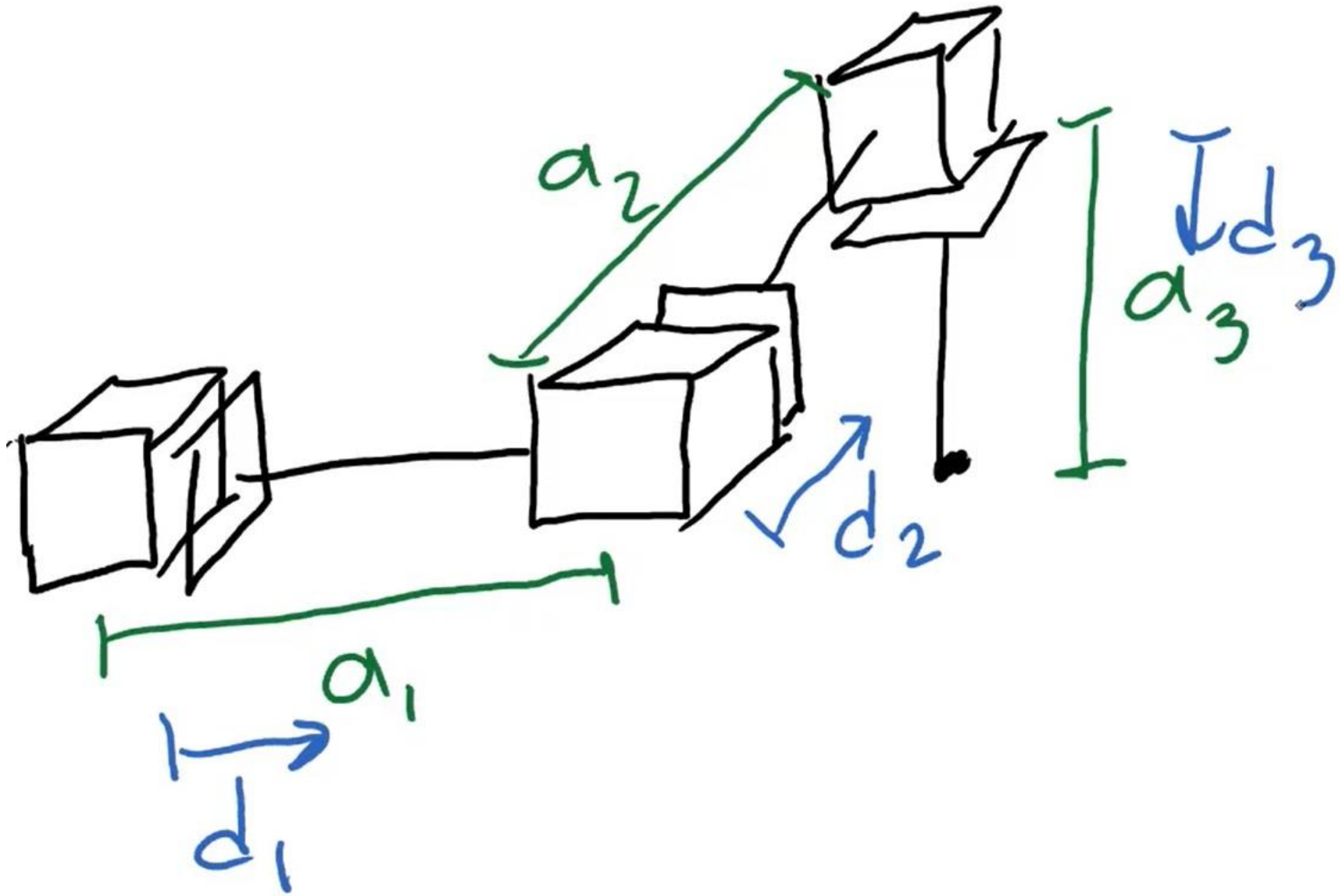




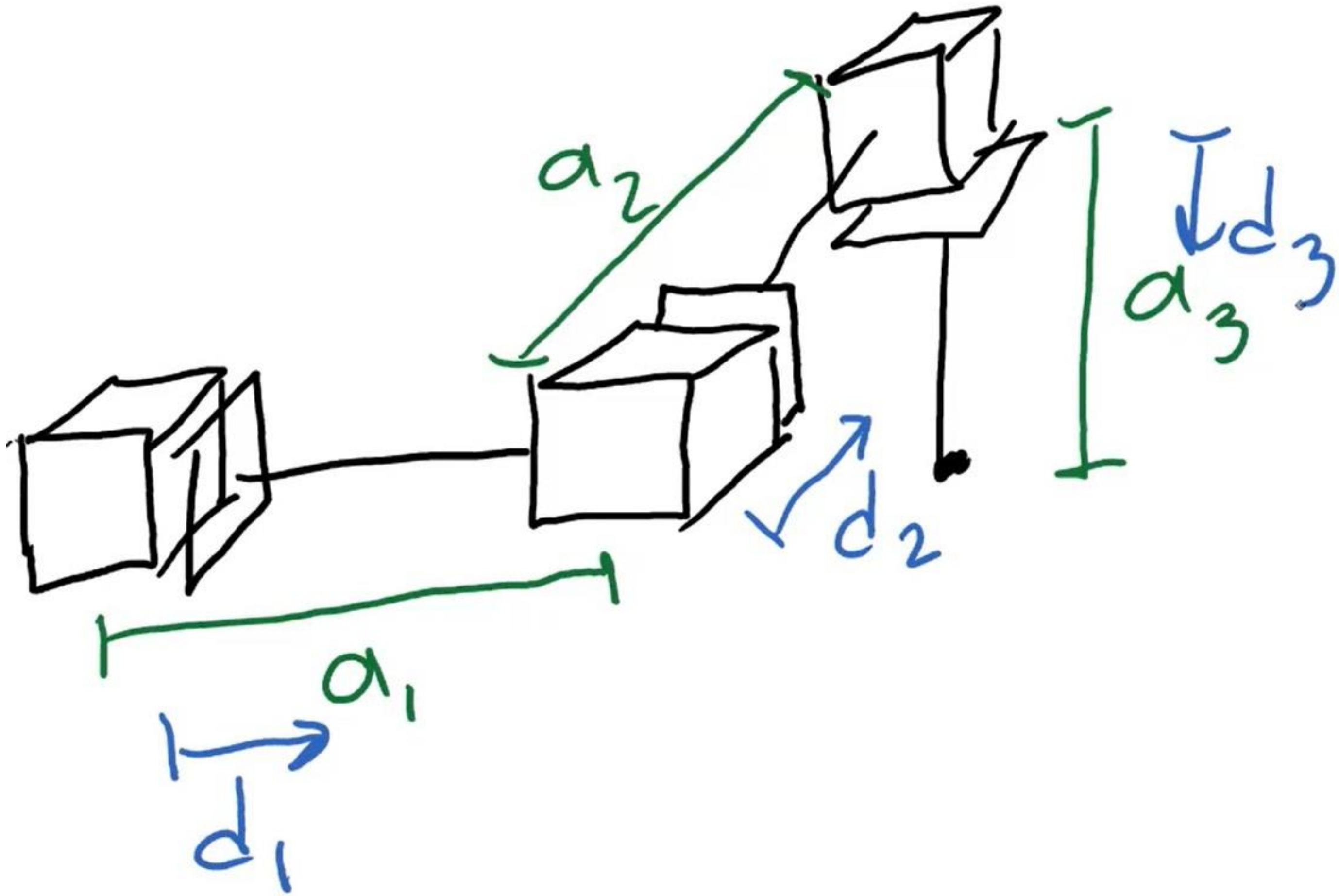
Cartesian Manipulator (Kinematic Diagram)



Cartesian Manipulator (Kinematic Diagram)

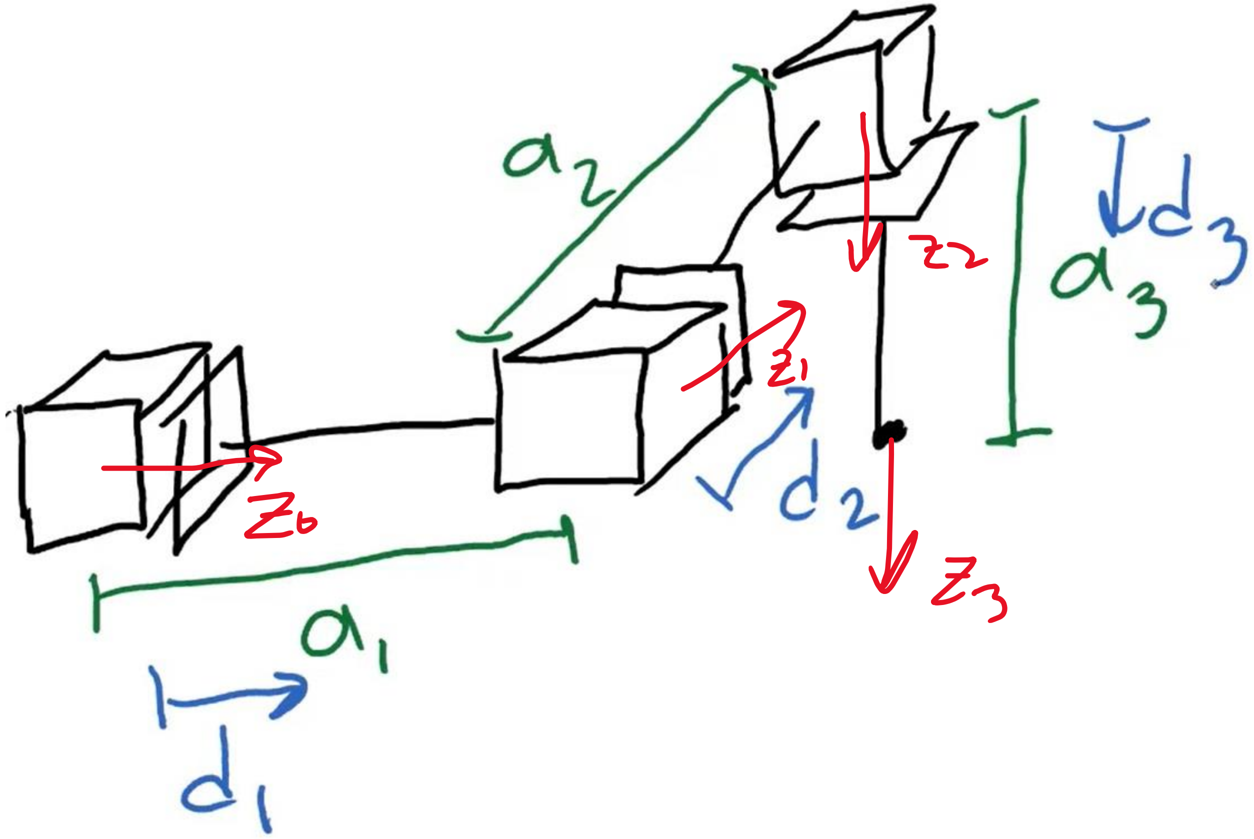


Cartesian Manipulator (Kinematic Diagram)



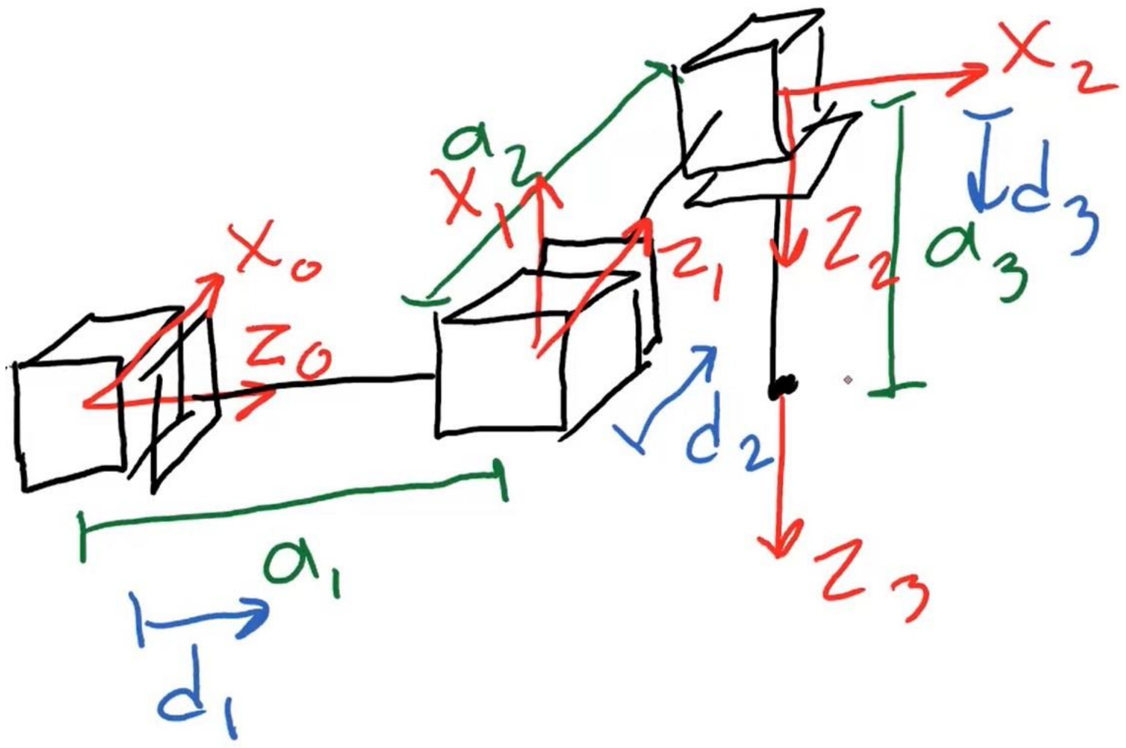
Cartesian Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#01



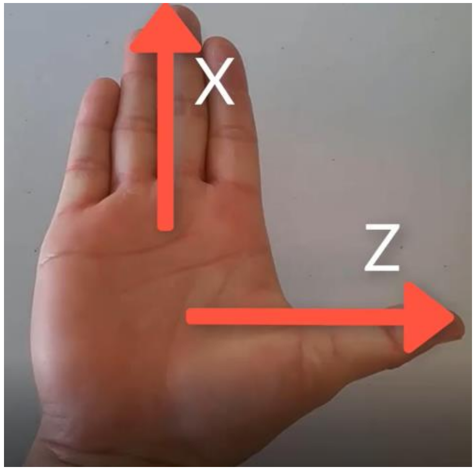
Cartesian Manipulator (Kinematic Diagram)

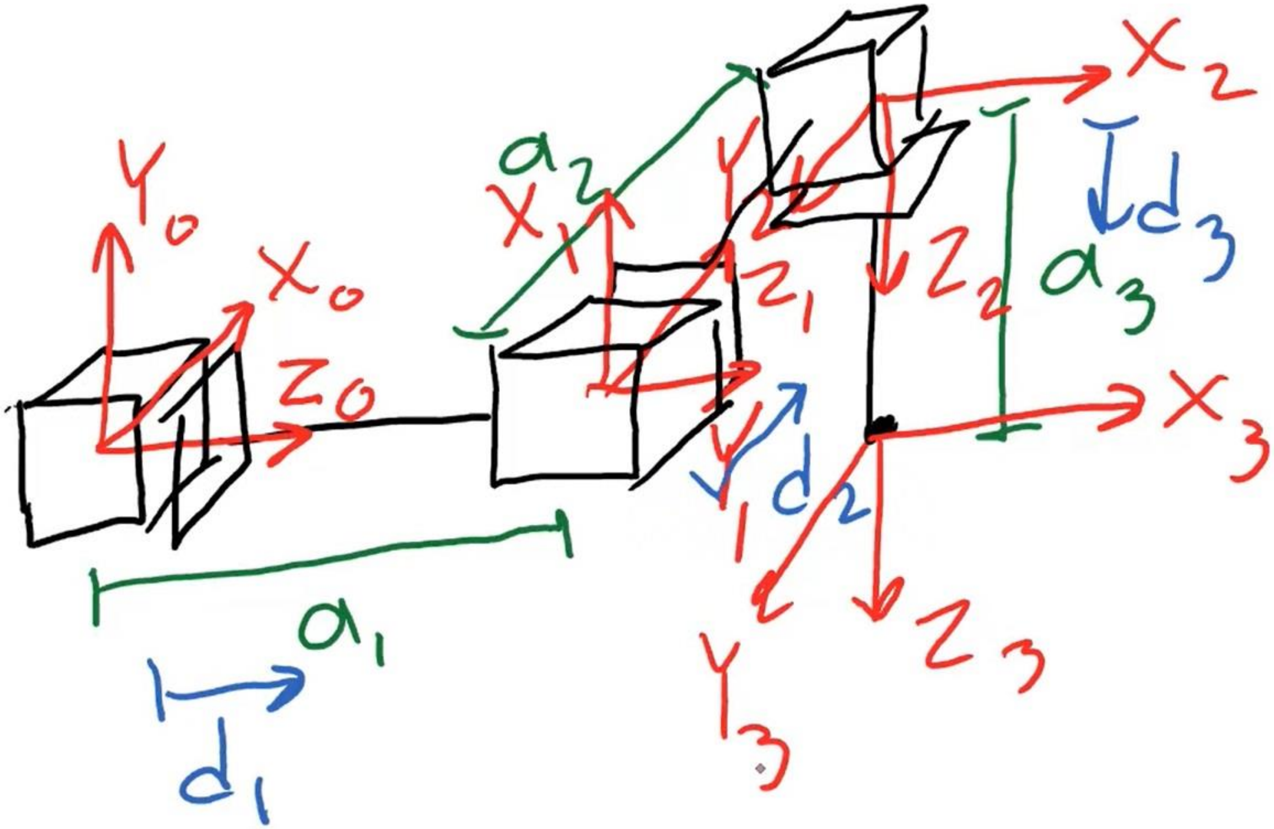
- Denavit-Hartenberg Rule#02



Cartesian Manipulator (Kinematic Diagram)

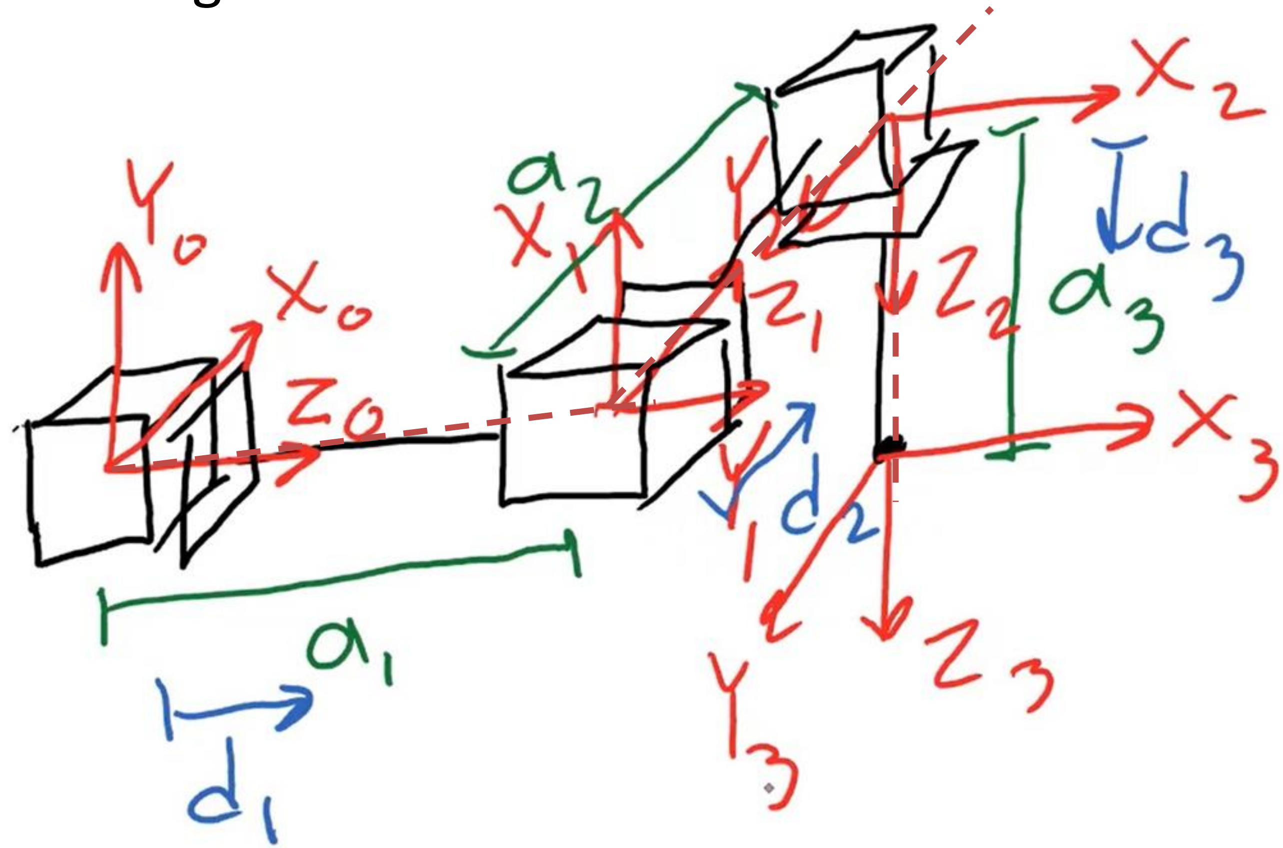
- Denavit-Hartenberg Rule#03





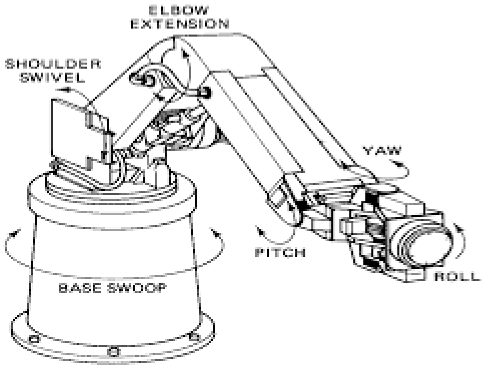
Cartesian Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#04 ok for all frames.

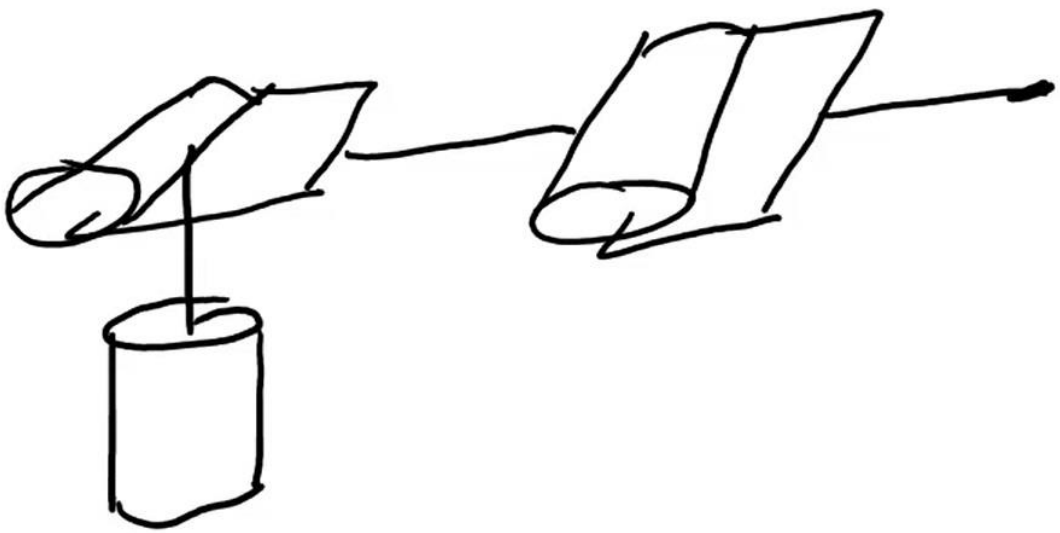


Articulated Manipulator

- **Articulated Robot's** mechanical movement and configuration closely **resemble** a **human arm**.
- The arm is mounted to a **base** with a **twisting joint**.
- The arm itself can **feature anywhere** from **two rotary** joints up to **ten rotary joints** which act as axes, with each additional joint or axis allowing for a greater degree of motion.
- Typical applications for Articulated Robots are **assembly**, **arc welding**, **material handling**, **machine tending**, and **packaging**.

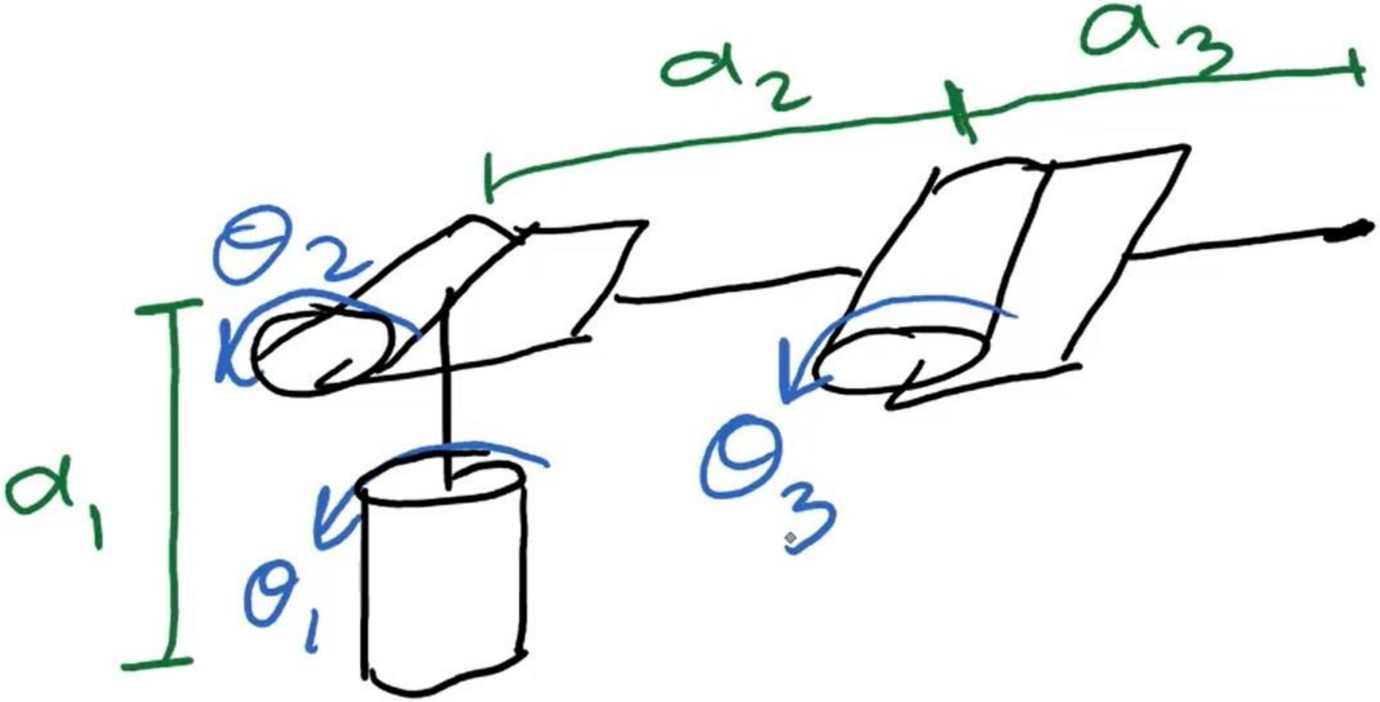


Articulated Manipulator (Kinematic Diagram)



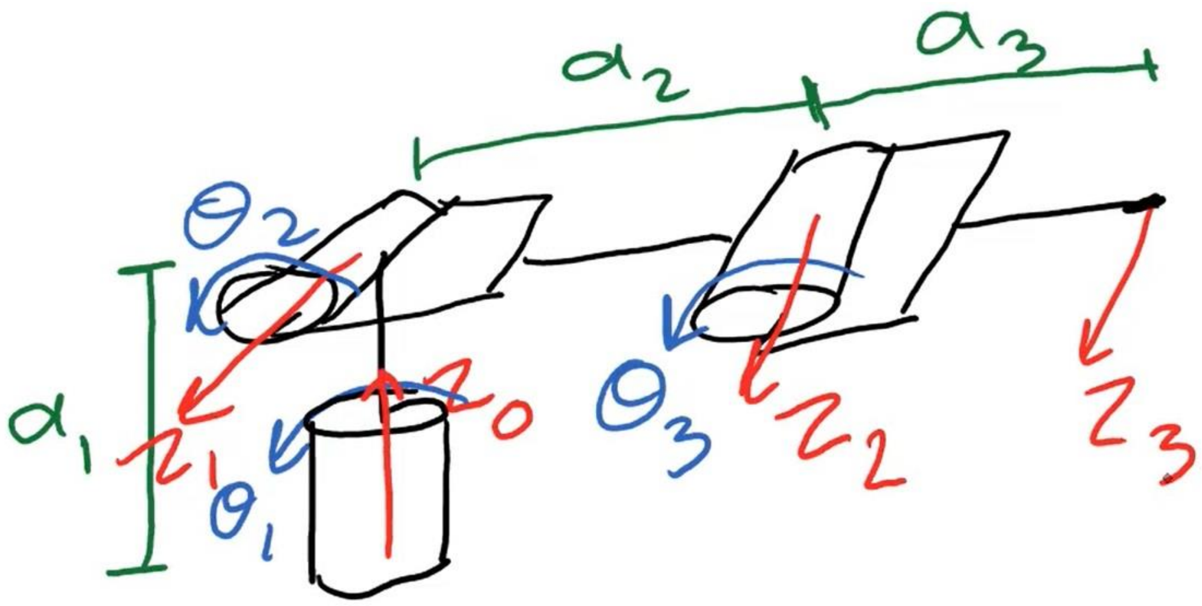
Articulated Manipulator (Kinematic Diagram)

- Three Links a_1, a_2 and a_3, with three joint variables Θ_1, Θ_2, Θ_3.



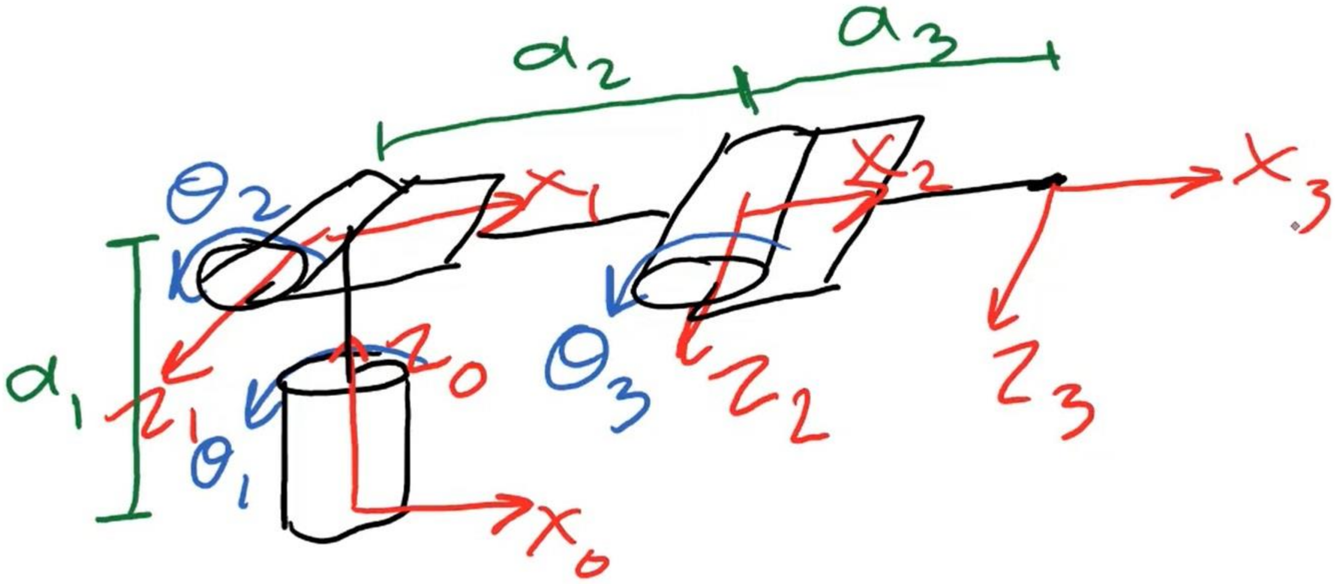
Articulated Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#01



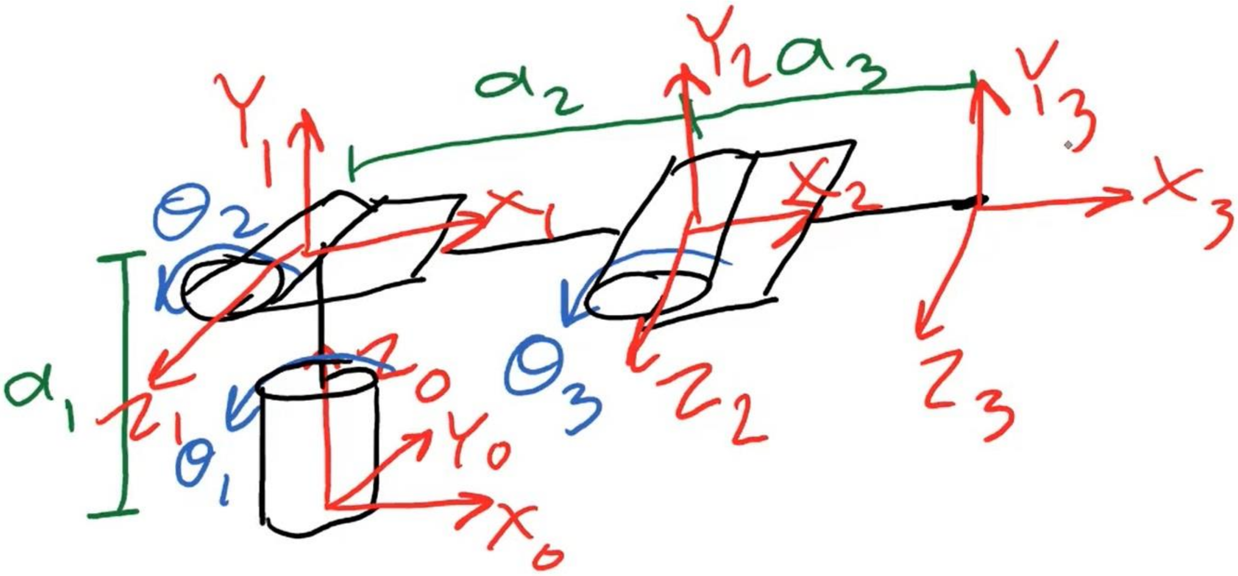
Articulated Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#02



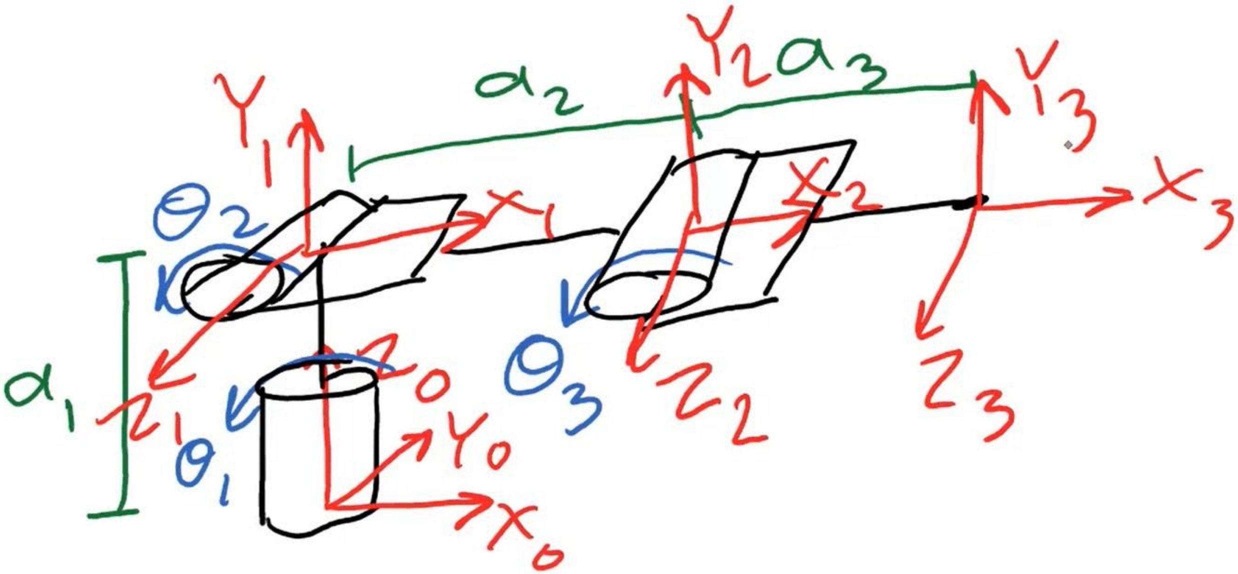
Cartesian Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#03



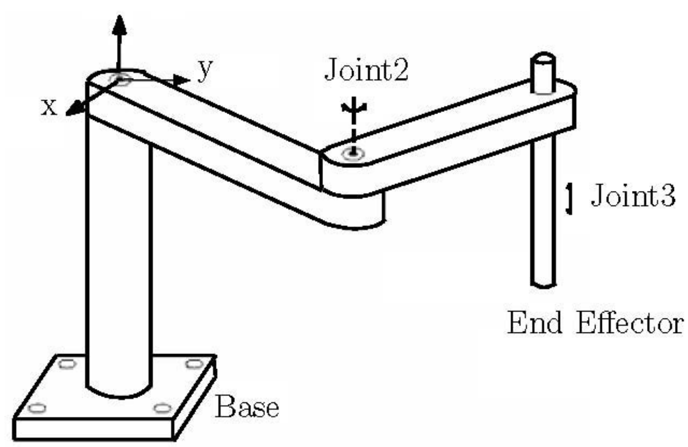
Cartesian Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#04

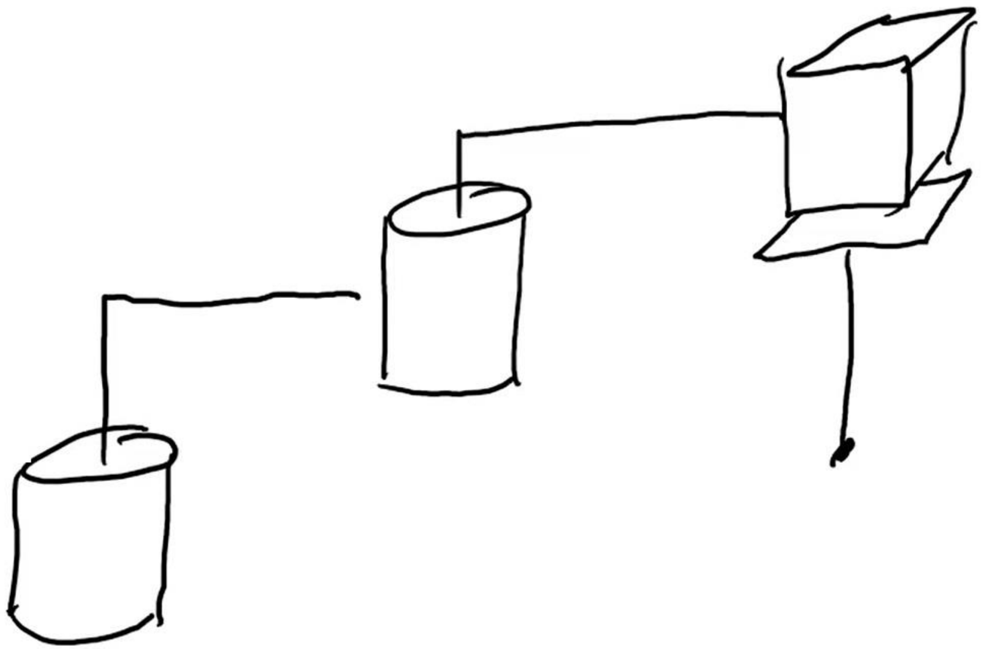


SCARA Manipulator

- **SCARA** is an acronym that stands for **Selective Compliance Assembly Robot Arm** or **Selective Compliance Articulated Robot Arm.**
- SCARA Robots function on **3-axis** (**X, Y,** and **Z**), and have a **rotary motion** as well.
- SCARA Robots excel in **lateral movements** and are commonly **faster moving** and have easier integration **than Cartesian** Robots.
- Typically, SCARA robots are used for **assembly** and **palletizing**, as well as **bio-med** application.

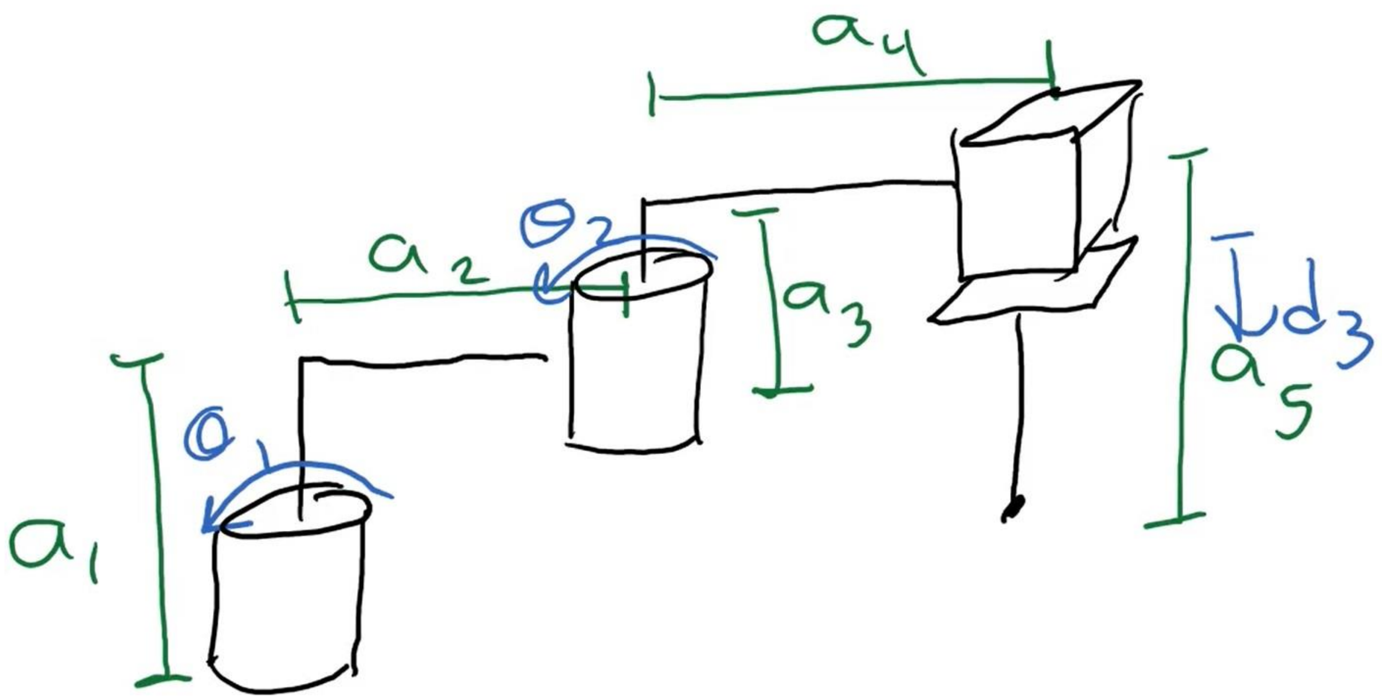


SCARA Manipulator (Kinematic Diagram)



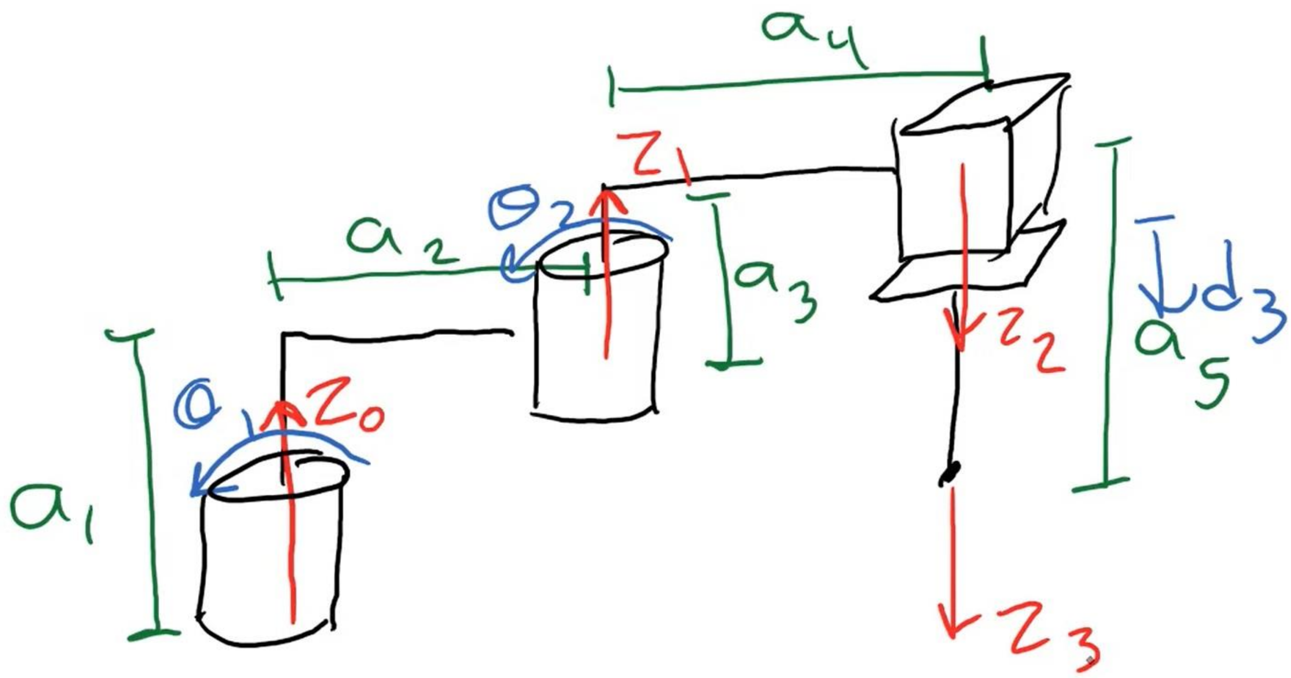
SCARA Manipulator (Kinematic Diagram)

- Five Links a_1, a_2, a_3, a_4, and a_5 with three joint variables θ_1, θ_2, d_3.



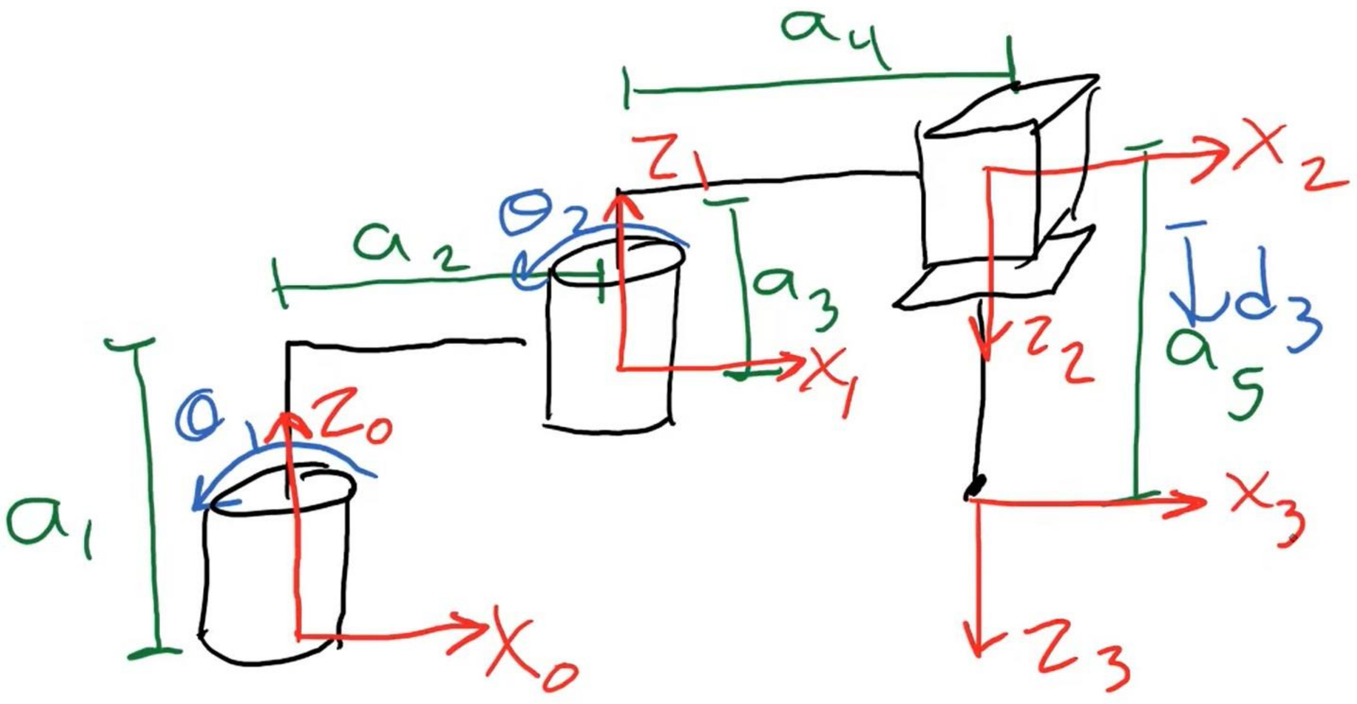
SCARA Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#01



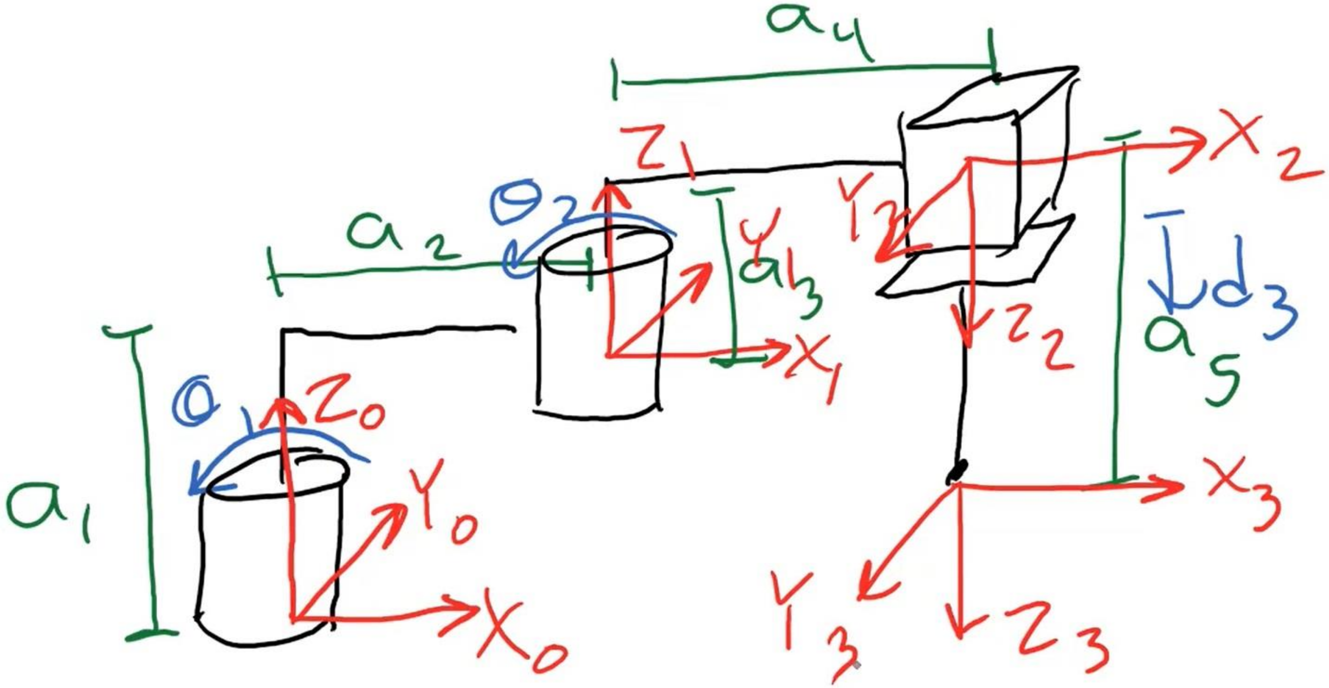
SCARA Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#02



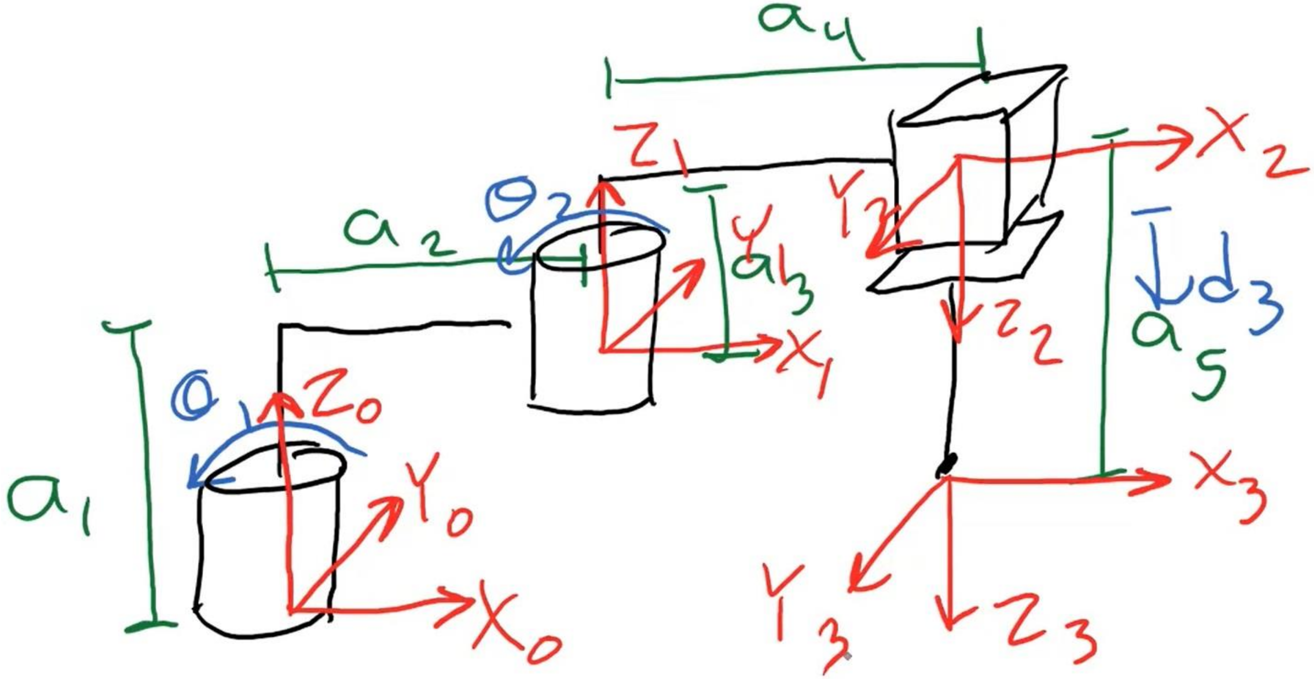
SCARA Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#03



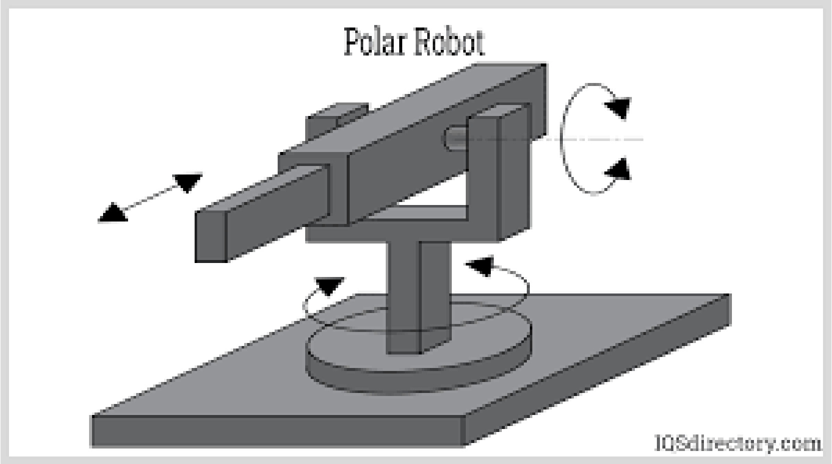
SCARA Manipulator (Kinematic Diagram)

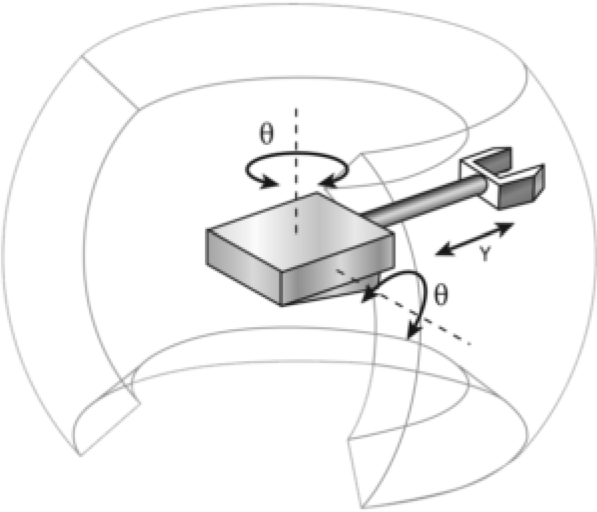
- Denavit-Hartenberg Rule#04, all ok.



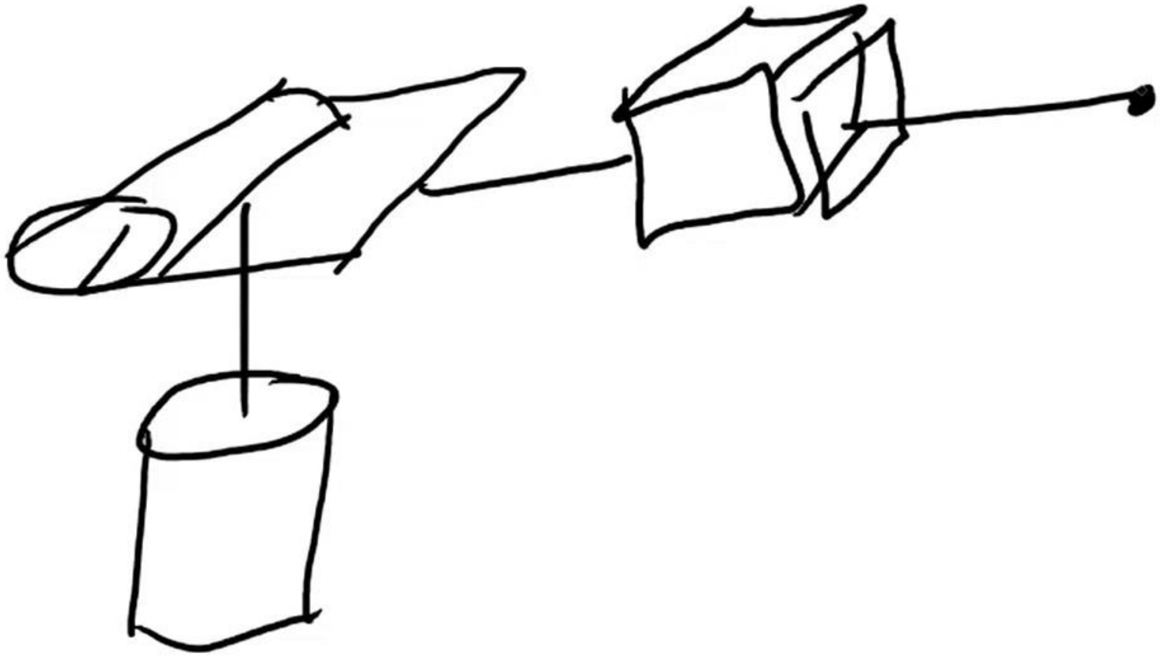
Spherical Manipulator

- **Polar** Robots, or **spherical robots**, have an arm with **two rotary joints** and **one linear joint** connected to a base with a twisting joint.
- The axes of the robot work together to form a **polar or spherical coordinate**, which allows the robot to have a **spherical work envelope**.
- Polar Robots are credited as one of the **first types of industrial robots to ever** be developed.
- Polar robots are commonly used for **die casting**, **injection molding**, **welding**, and **material handling**.
- Spherical coordinate system needs **two angles** and **a radius**.



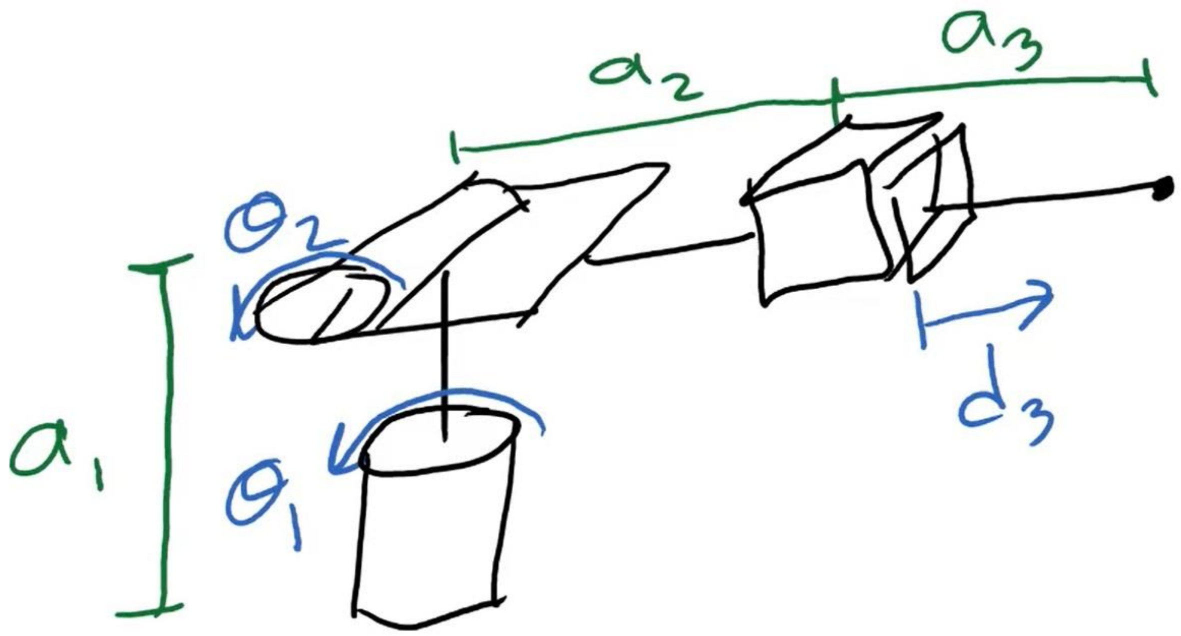


SCARA Manipulator (Kinematic Diagram)



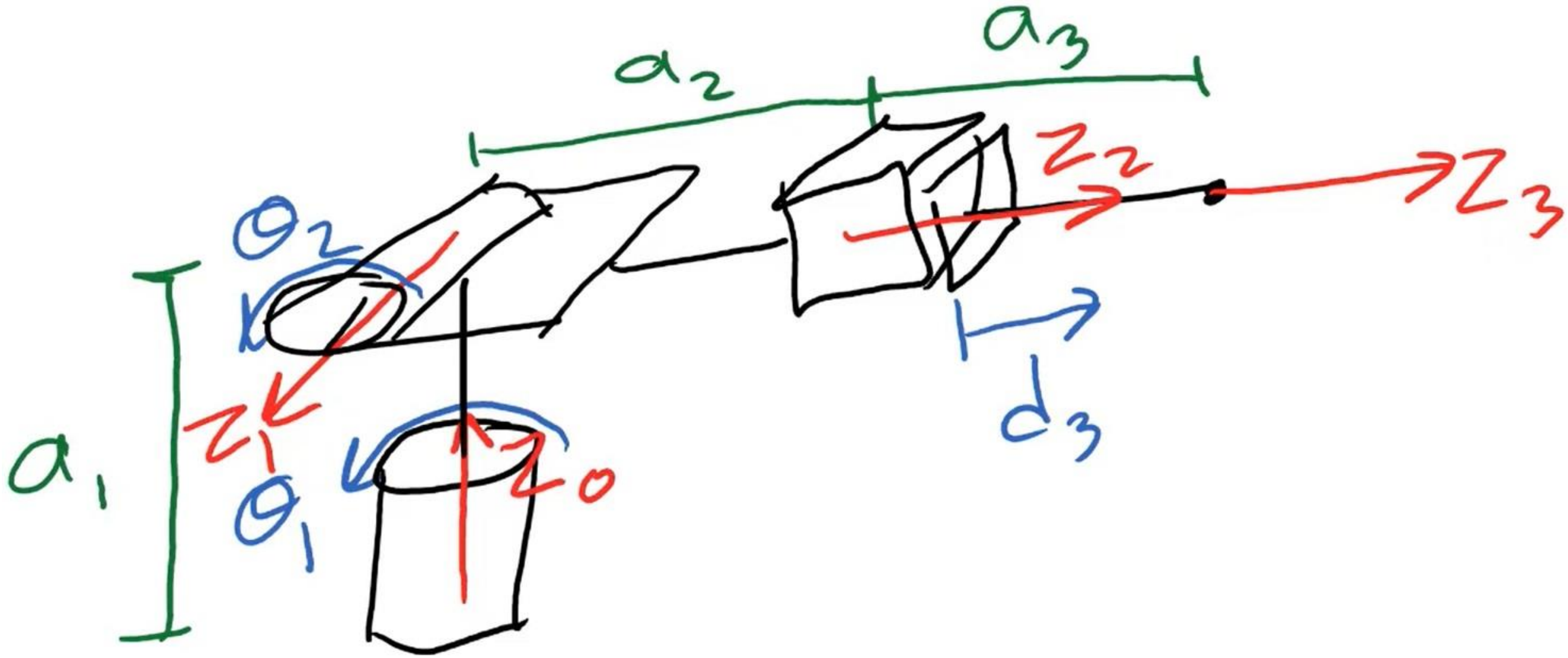
Spherical Manipulator (Kinematic Diagram)

- Three Links a_1, a_2 and a_3, with three joint variables Θ_1, Θ_2, d_3.



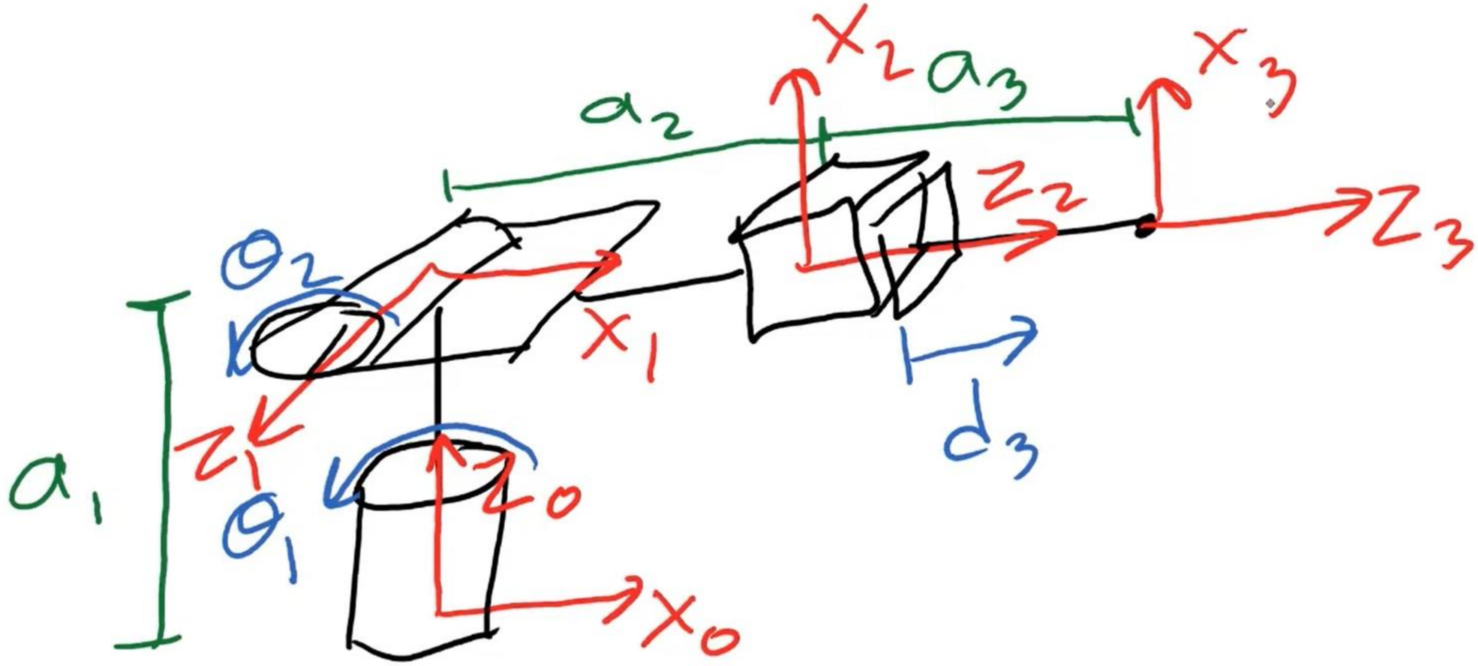
Spherical Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#01



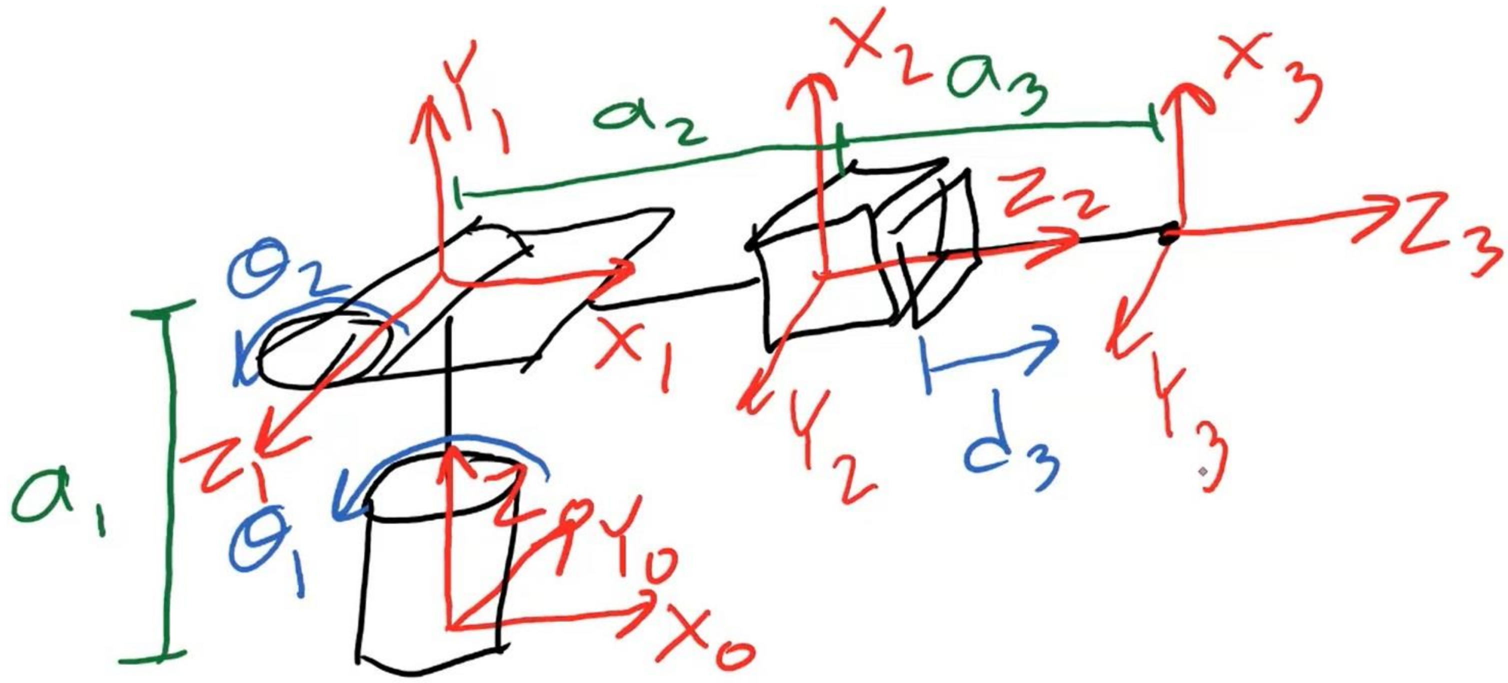
Spherical Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#02



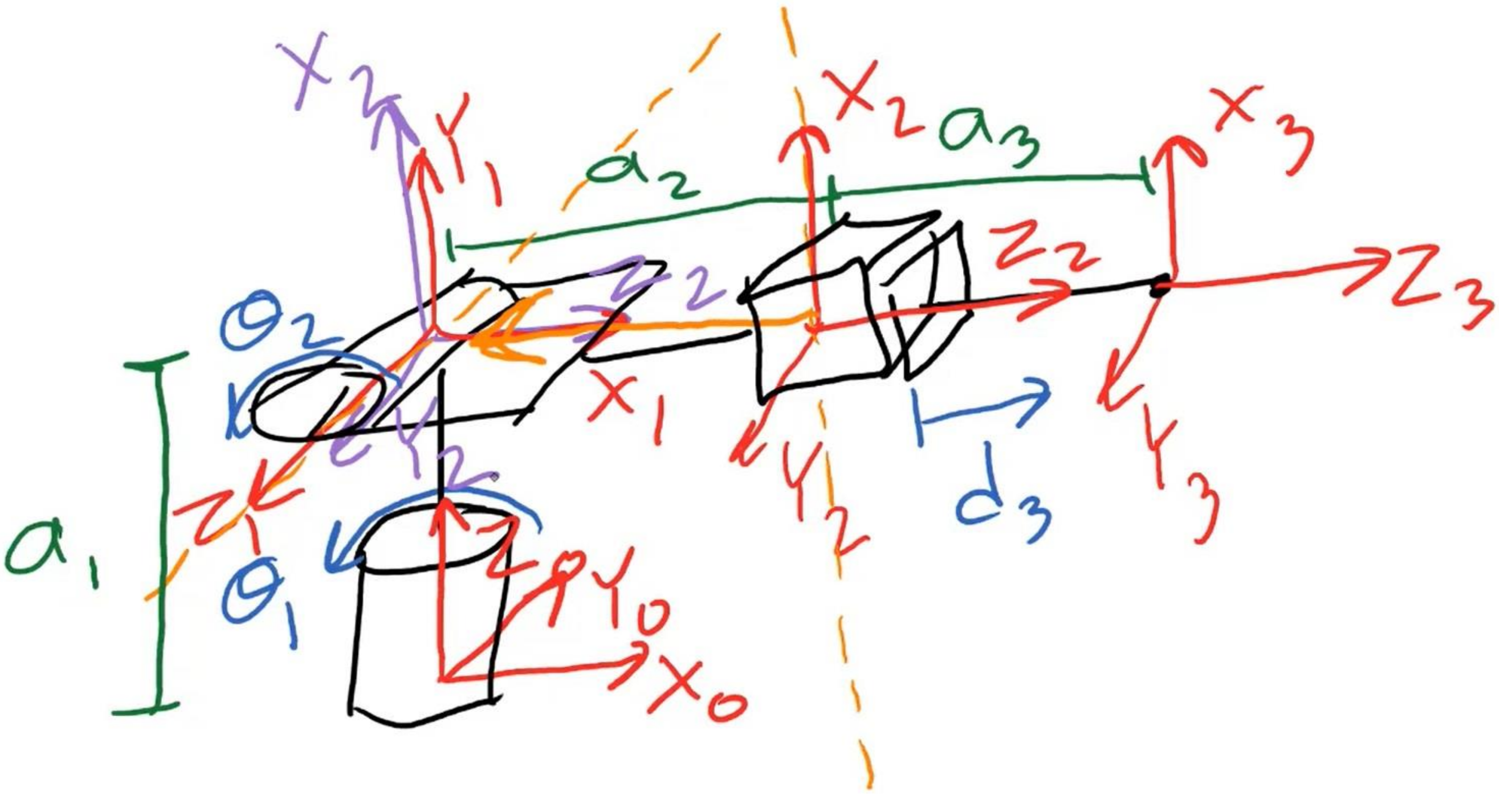
Spherical Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#03



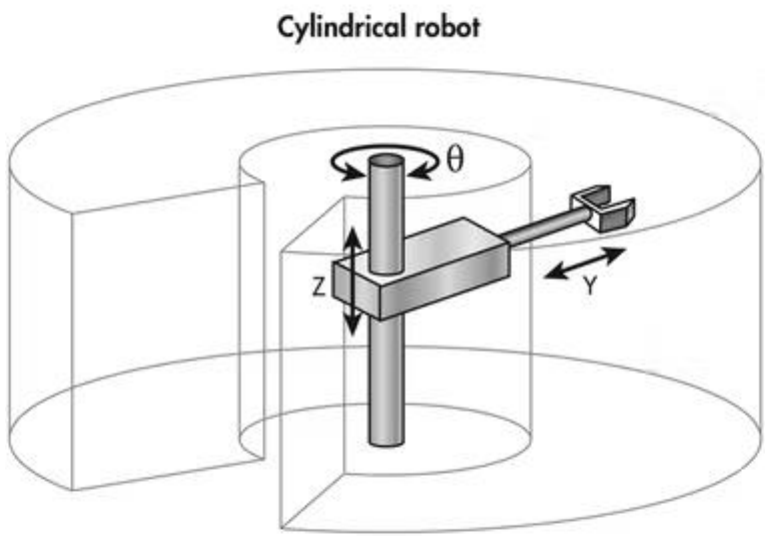
Spherical Manipulator (Kinematic Diagram)

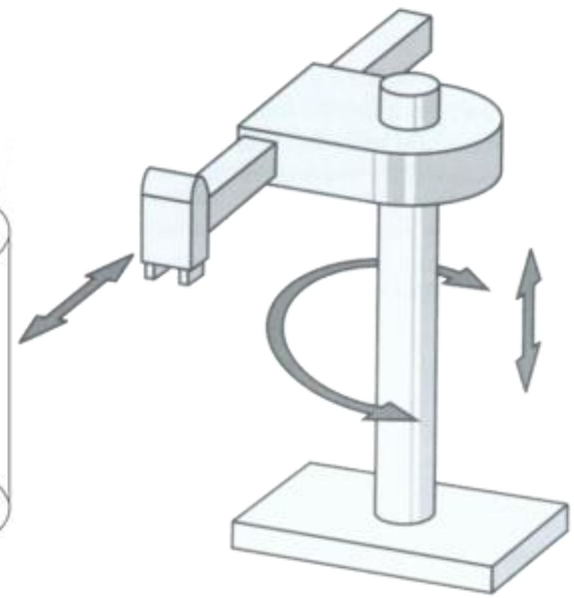
- Denavit-Hartenberg Rule#04. X_1 is parallel to Z_2



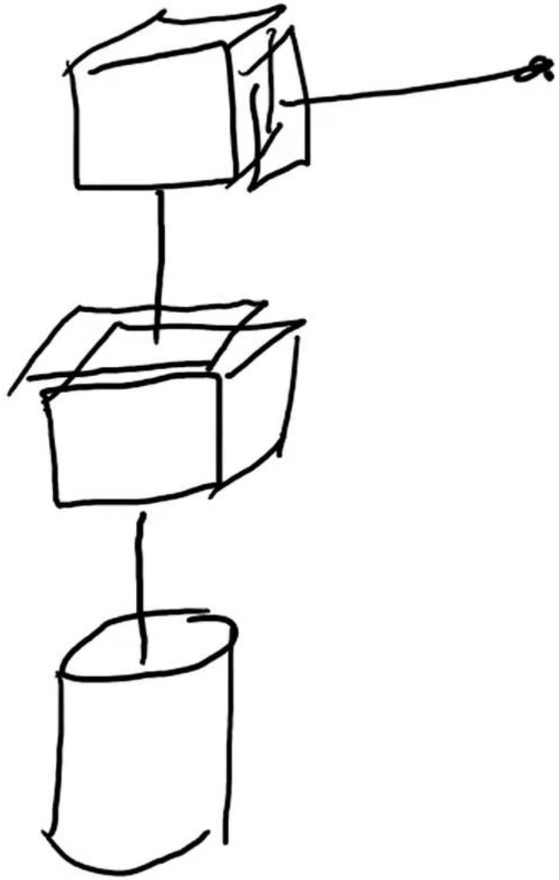
Cylindrical Manipulator

- **Cylindrical Robots** have **a rotary joint** at the base and **a prismatic joint** to connect the links.
- The robots have a cylindrical-shaped work envelope, which is achieved with **a rotating shaft and an extendable arm that moves in a vertical and sliding motion**.
- Cylindrical Robots are often used in tight workspaces for **simple assembly**, **machine tending**, or **coating applications** due to their **compact design**.



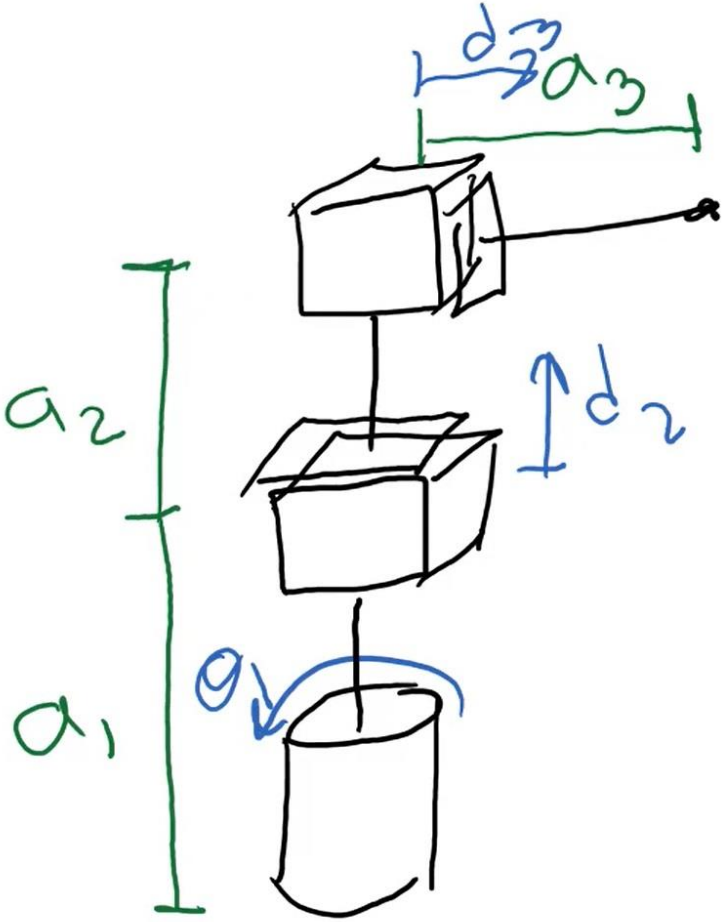


Cylindrical Manipulator (Kinematic Diagram)



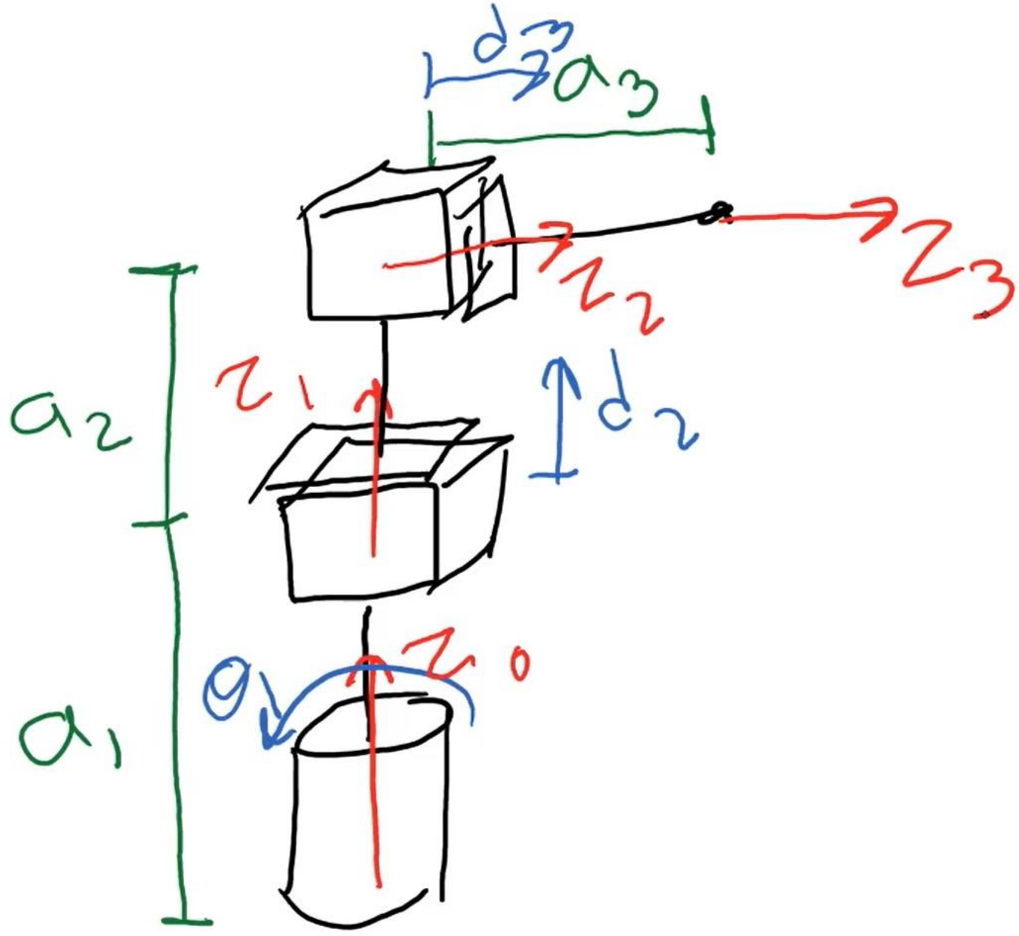
Cylindrical Manipulator (Kinematic Diagram)

- Three joints a_1, a_2, and a_3.
- There are three joint variables Θ_1, $\mathbf{d_2}$, and $\mathbf{d_3}$.



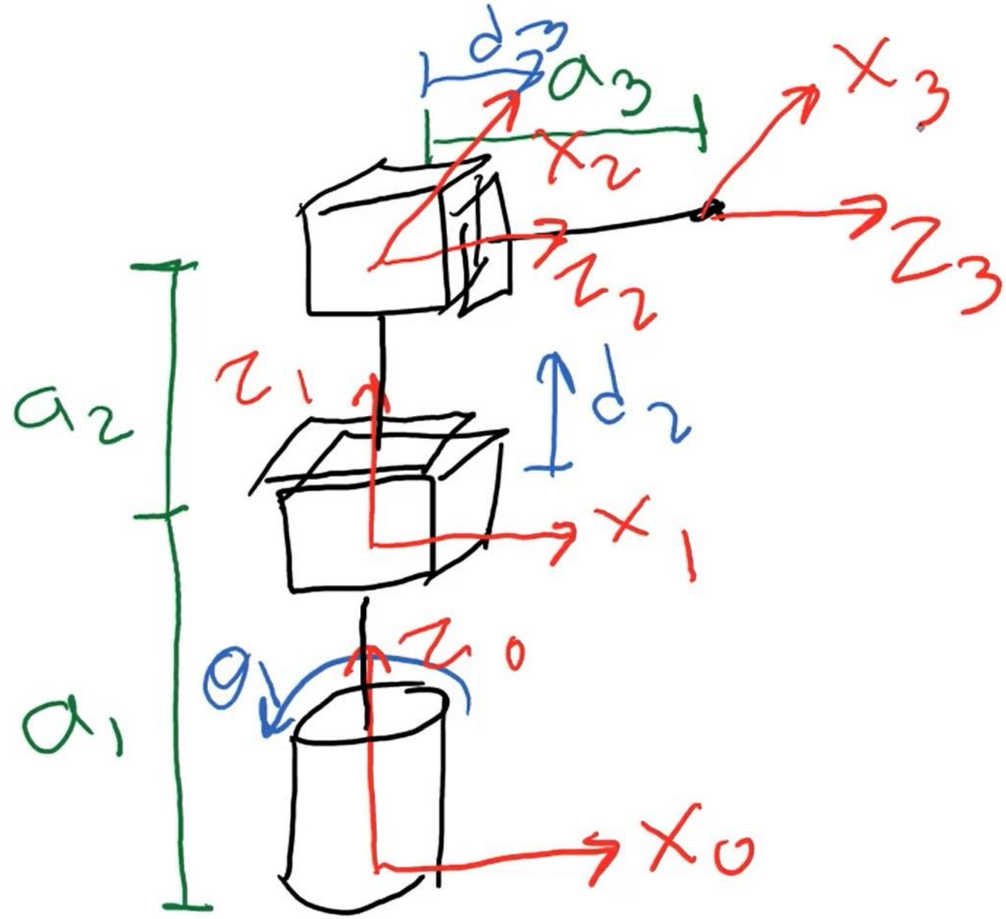
Cylindrical Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#01



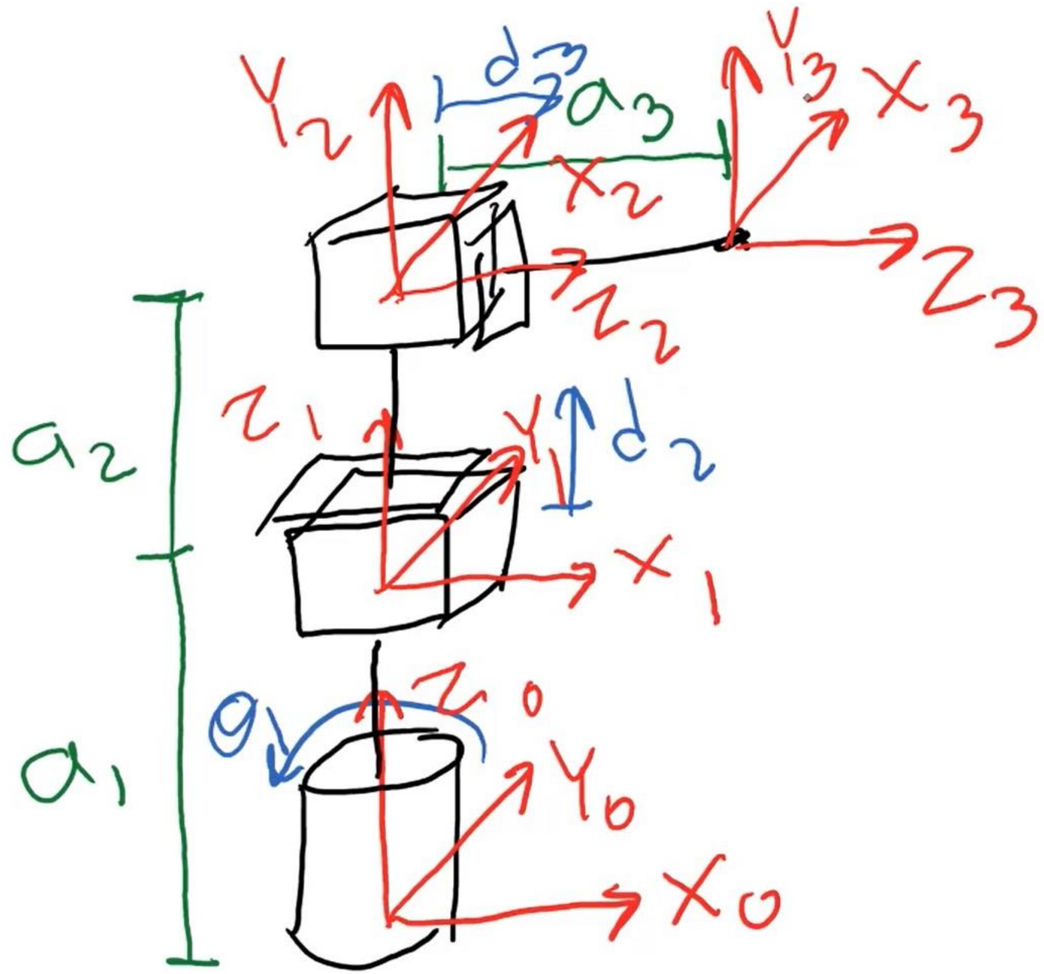
Cylindrical Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#02



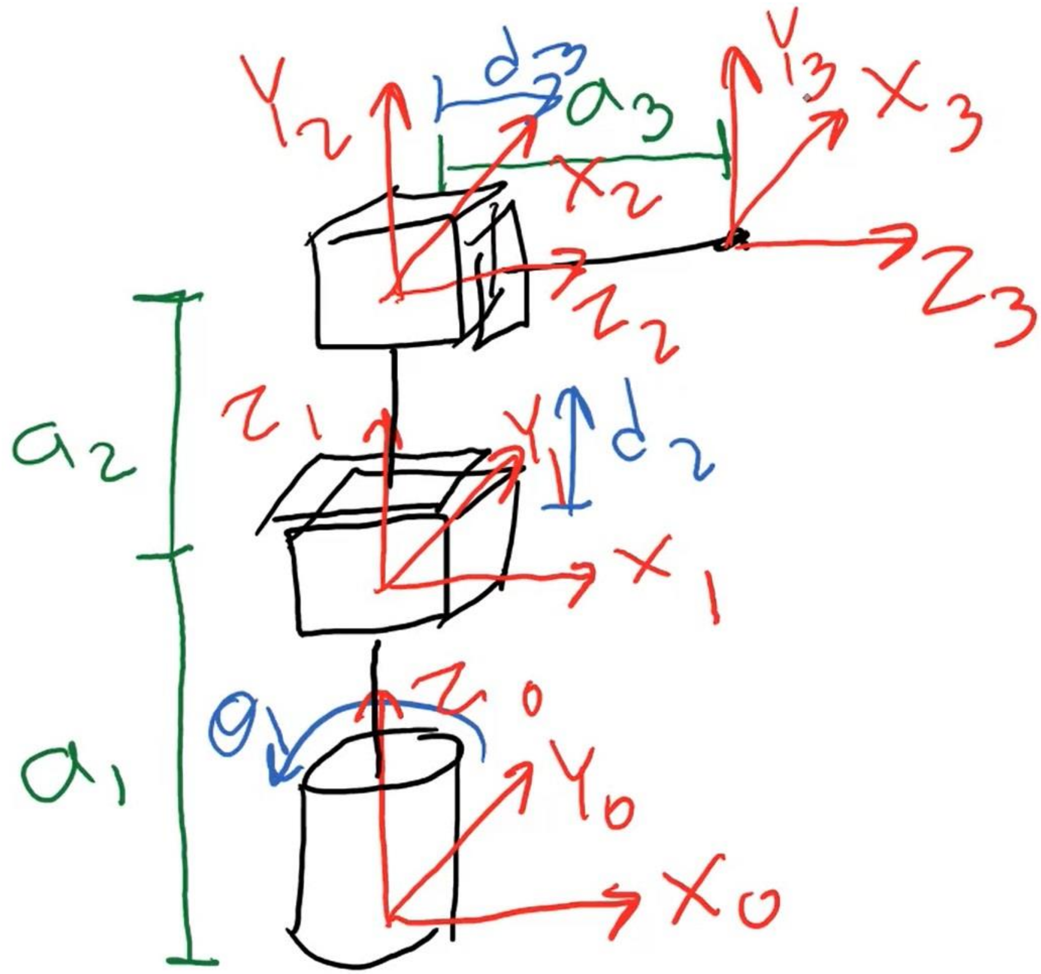
Cylindrical Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#03

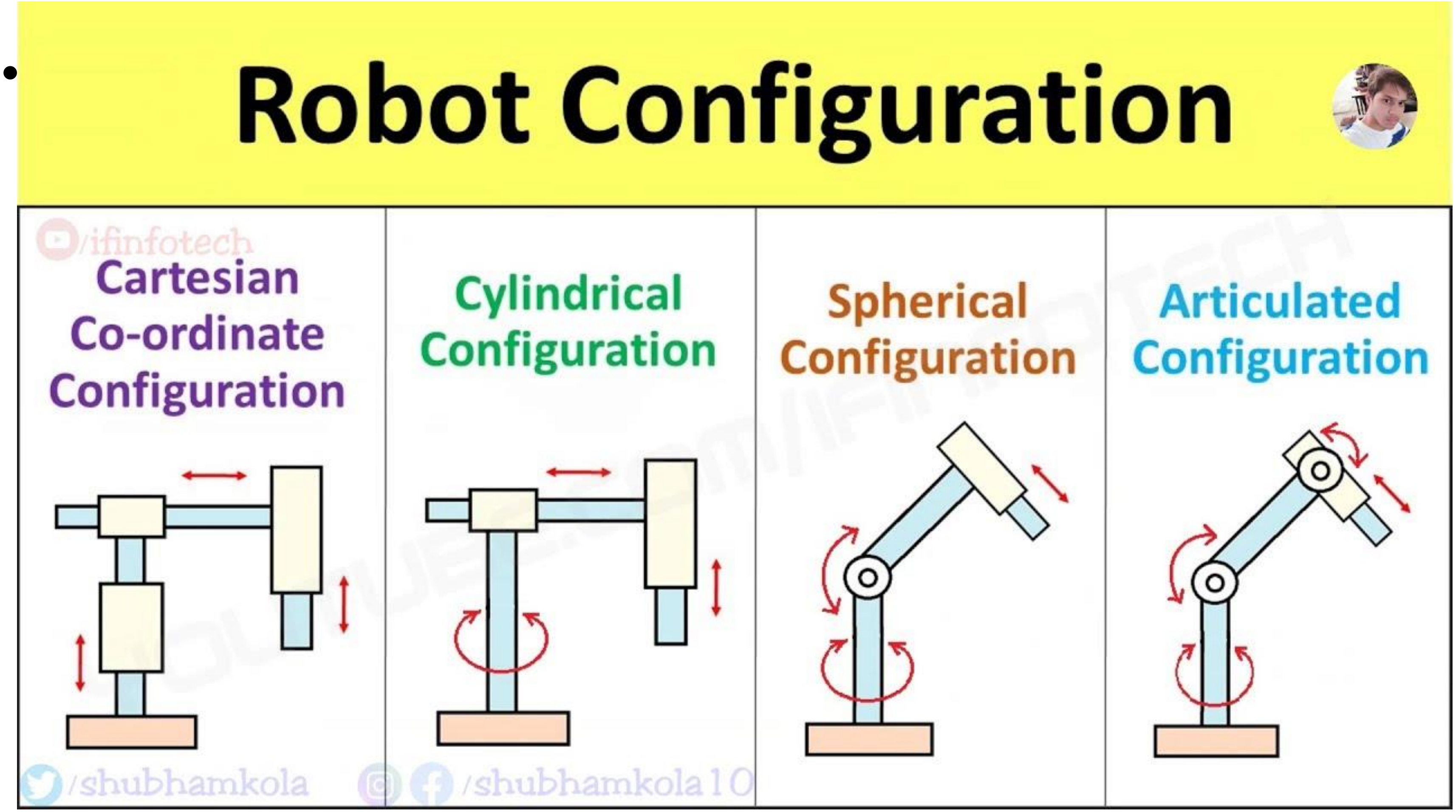


Cylindrical Manipulator (Kinematic Diagram)

- Denavit-Hartenberg Rule#04
- Ok for rule#04.

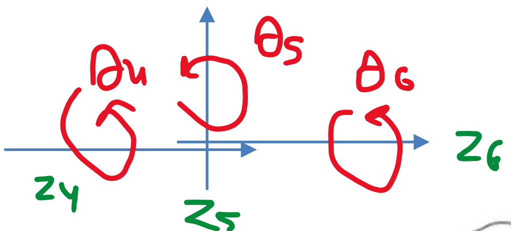


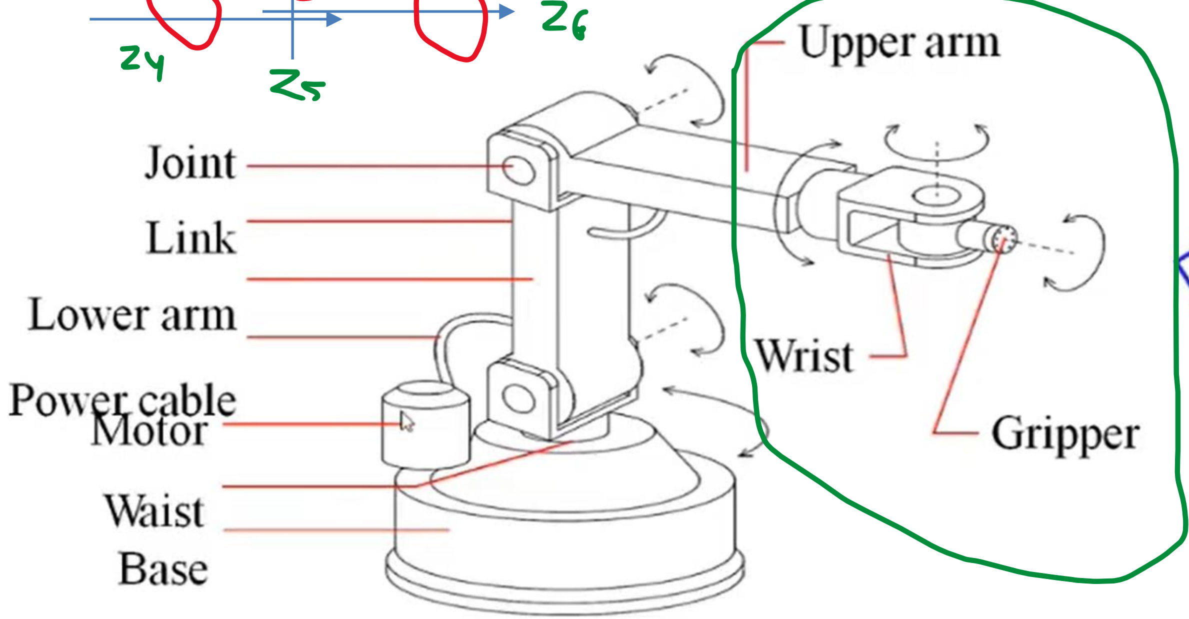
Manipulators Configurations

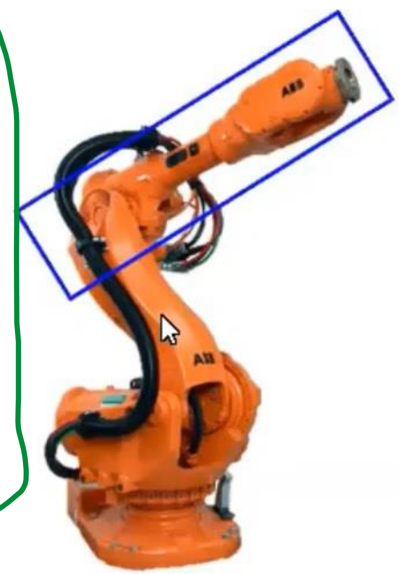
- 

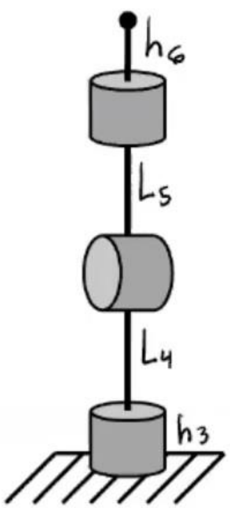
Spherical Wrist of a 6 DoF Manipulator

- **Spherical wrist**: A **three degree of freedom rotational joint** with all **three axes** of rotation crossing at a point is typically called a spherical wrist.
- Many **6 DoF** manipulators are made of **standard 3 DoF** manipulators plus placing a spherical wrist on them.
- Three revolute joints with intersecting z-axes, regardless of joint variables Θ_4, Θ_5 and Θ_6.









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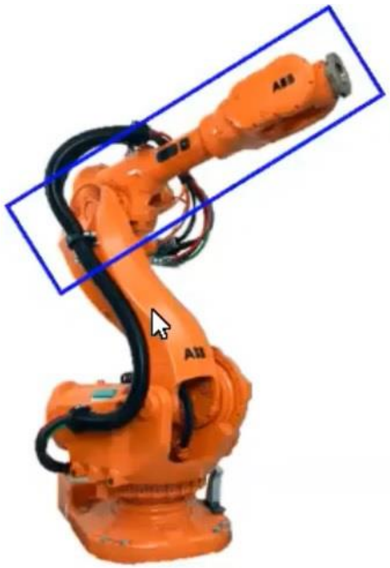

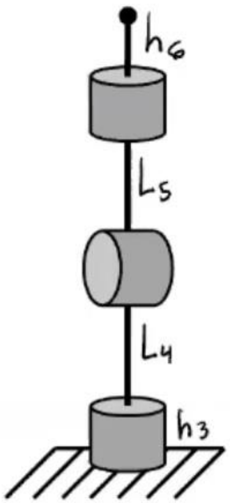

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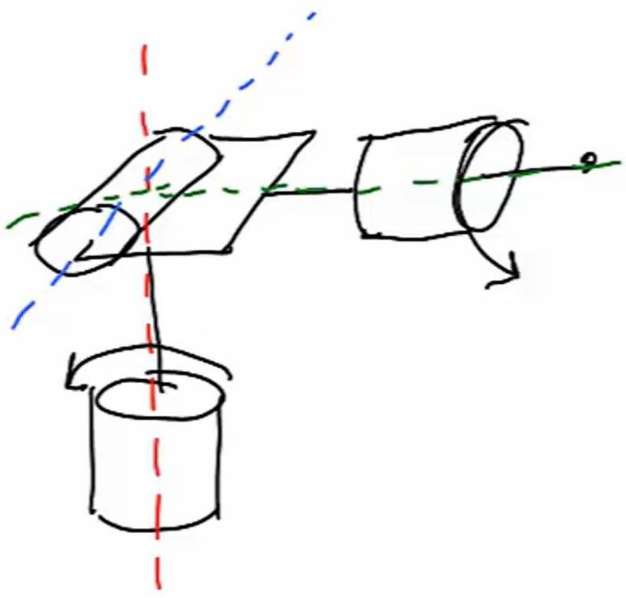

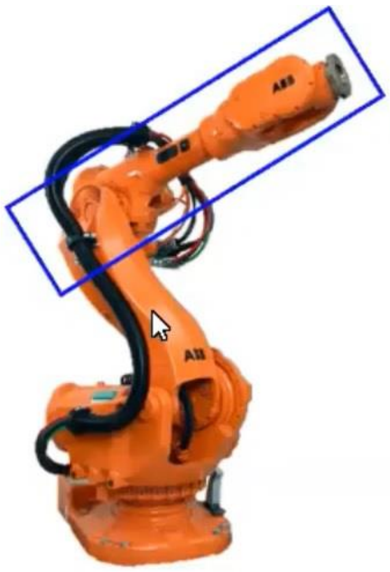

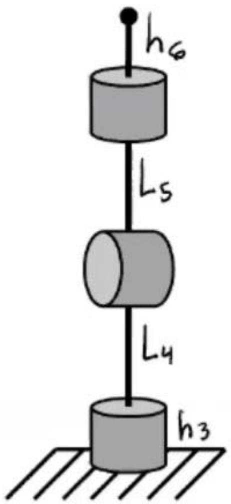

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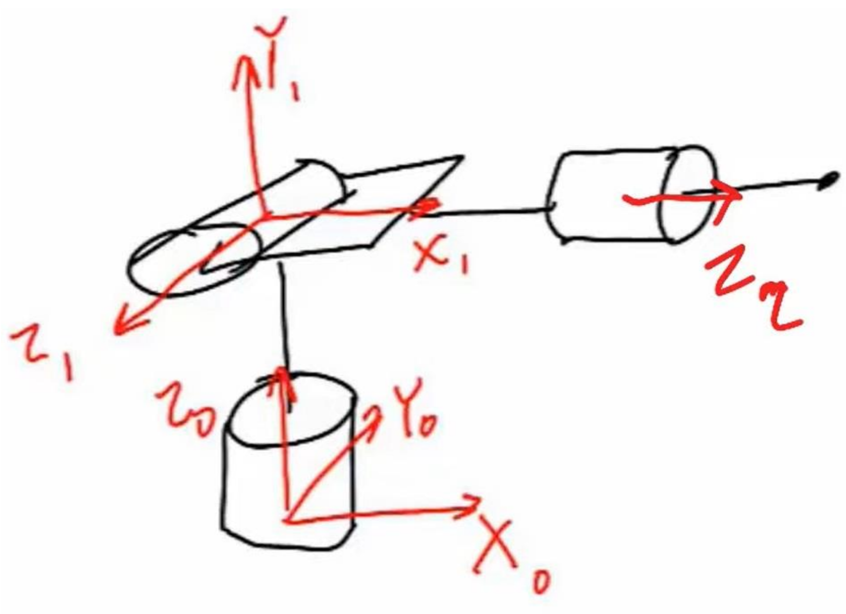

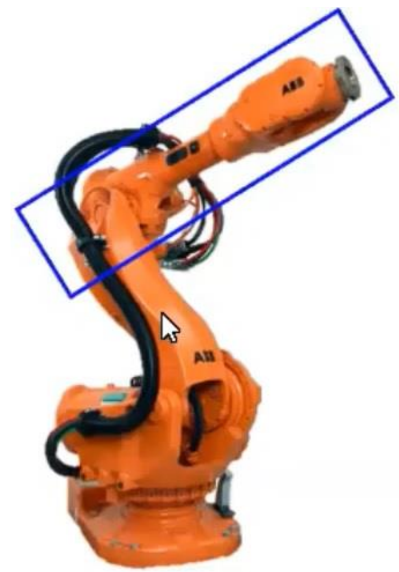

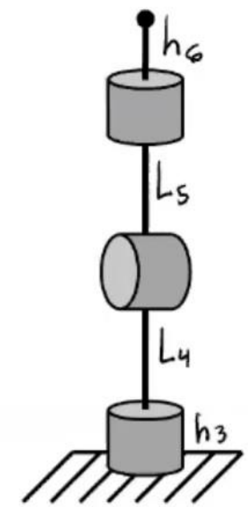

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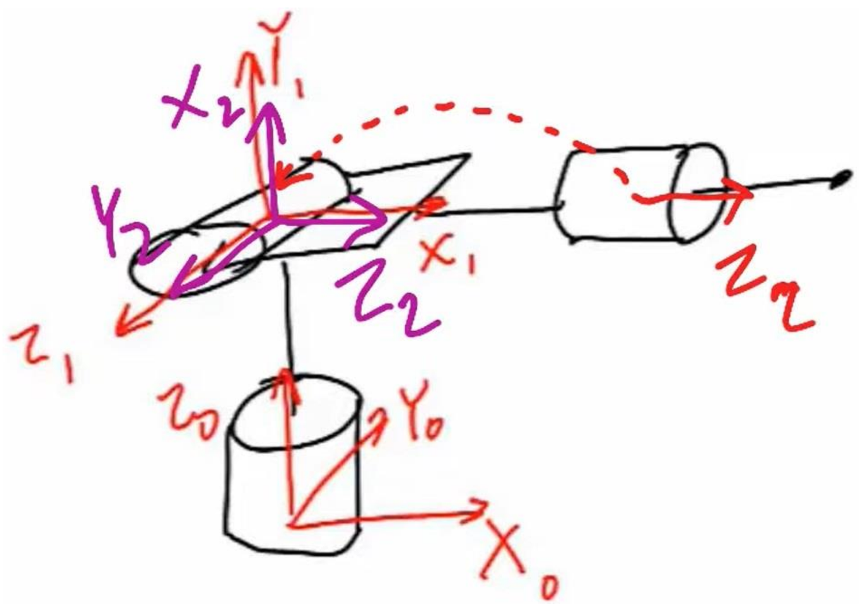
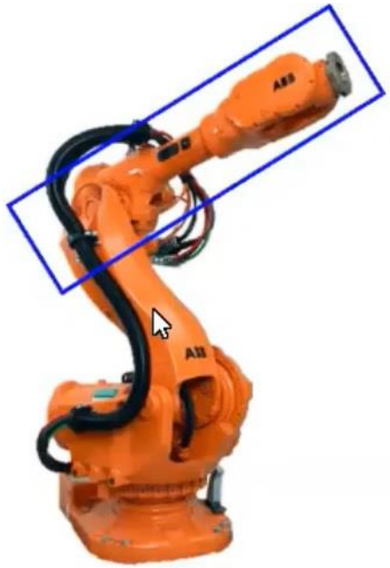
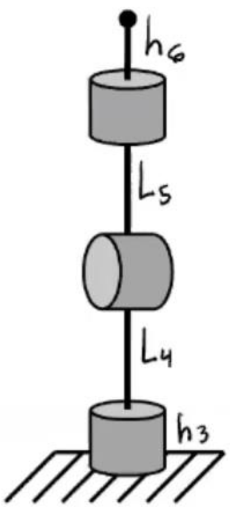
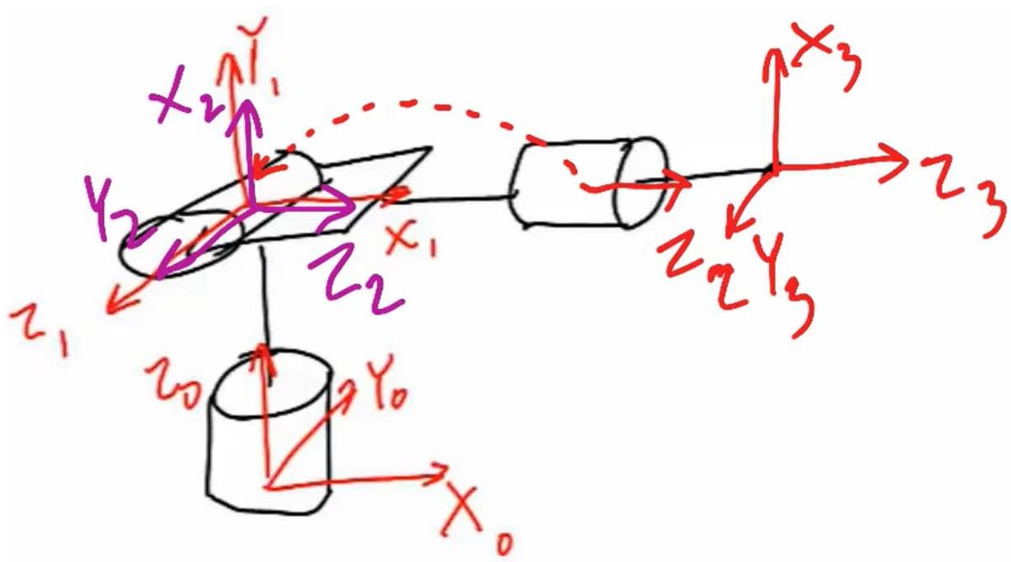


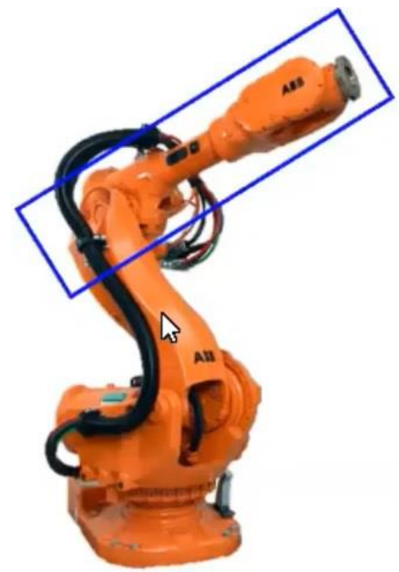


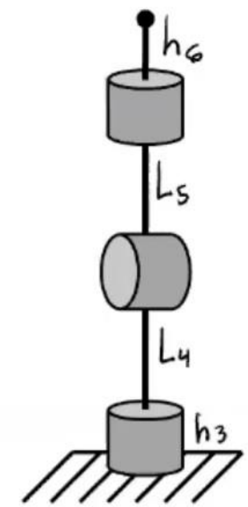


Spherical Wrist of a 6 DoF Manipulator

- **Spherical wrist**: A **three degree of freedom rotational joint** with all **three axes** of rotation crossing at a point is typically called a spherical wrist.
- $\mathbf{Z_2}$ is **not intersecting** $\mathbf{X_1}$ as both are **parallel**. Parallel lines never intersect each other.







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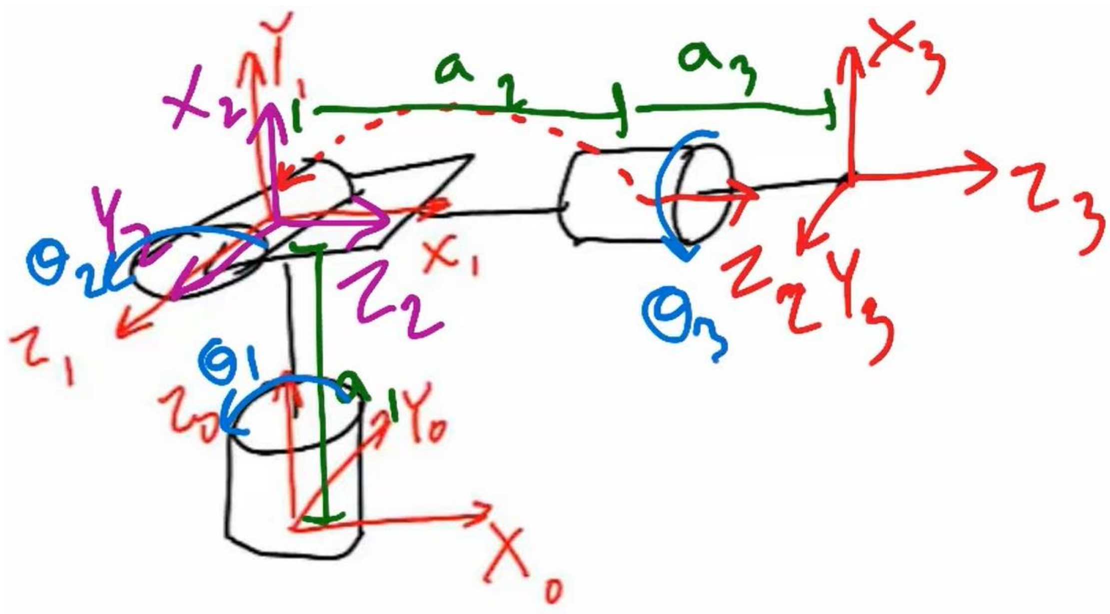

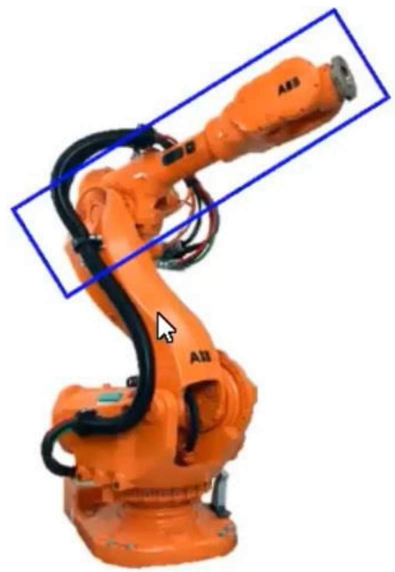

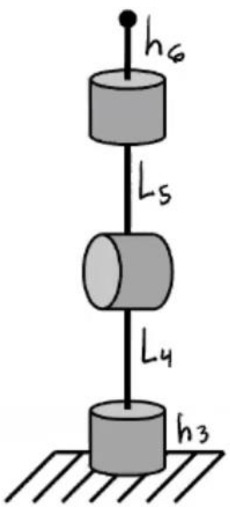

End